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Acoustics in communal libraries: common problems and their solutions

School of Electrical Engineering

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Kunnallisten kirjastojen käyttötavat ja palvelut, sekä niistä syntyvät äänet, ovat kehittyneet paljon viime vuosikymmeninä. Monista kirjastoista on muutosten myötä tullut hälyisiä ja rauhattomia, sillä tilan akustiikkaa ei ole muokattu nykyiseen tilanteeseen sopivaksi. Tässä työssä tutkittiin syntyneitä akustisia ongelmia ja esitettiin niihin ratkaisuja. Työ on tehty osana Yleisten kirjastojen muuttuva äänimaisema -projektia, jossa tutkittiin viittä kirjastoa eri puolilta Suomea.

Tutkittujen kirjastojen akustiset ongelmat voidaan jakaa viiteen ryhmään: äänen leviäminen lasten- ja nuortenosastoilta muualle kirjastoon, äänen leviäminen kerroksesta toiseen, taustaäänitaso, jälkikaiunta ja ääneneristys. Näitä ominaisuuksia mitattiin kussakin kirjastossa ja tuloksia verrattiin soveltuvin osin sekä suosituksiin että kirjastohenkilökunnan kokemuksiin. Lisäksi tutkittiin kuuntelukokeen avulla henkilökunnan mieltymyksiä erilaisiin akustisiin ympäristöihin.

Selvästi suurin osa mittaustuloksista tuki hyvin yllämainittujen ongelmien olemassaoloa: suosituksista poikettiin tai ne täytettiin vain vaivoin. Kuuntelukoe puolestaan osoitti, että eri ihmiset pitävät erilaisista akustisista ympäristöistä kirjastossa. Ratkaisujen lähtökohtana oli kuitenkin kaikkien havaittujen ongelmien poistaminen.

Akustiikan parantamiseksi jälkikaiuntaa ja äänen leviämistä tulee kontrolloida. Kirjastojen tulee lisätä ääntä absorboivia materiaaleja esimerkiksi katto- ja seinäpinnoille, sijoittaa äänen leviämistä rajoittavia esteitä osastojen välille sekä nostaa taustaäänen voimakkuutta. Ääneneristystä vaativiin tiloihin tulisi vuorostaan rakentaa paksummat ja tiiviimmät seinärakenteet tai hankkia sopivat siirto- tai taittoseinät. Ratkaisujen toteutus täytyy suunnitella kirjastokohtaisesti, sillä tilat ovat vaihtelevia.

Kaiken kaikkiaan voidaan sanoa, että akustiikka on huomioitu kirjastoissa huonosti. Sen sunnitteluun tulee kiinnittää huomiota äänimaisemallisten ongelmien estämiseksi. Iso muutos tarvitaankin asenteessa: akustiikka on tärkeä osa kirjaston käytettävyyttä ja se tulee ottaa osaksi niin uudisrakentamista kuin remontointiakin.

Avainsanat: akustiikka, akustiikkasuunnittelu, jälkikaiunta, kirjasto, leviämisvaimennus, puheen ymmärrettävyys, STI, ääneneristys, äänimaisema

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ABSTRACT OF THE
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The uses and services of communal libraries, as well as their soundscapes, have developed considerably during the past decades. Along with the changes, many libraries have become noisy and restless, as the acoustics of the space has not been adapted to the current situation. In this thesis the resulting acoustic problems were investigated and the solutions for them were given. The work was a part of the project Changing Soundscape of Communal Libraries where five libraries across Finland were studied.
The acoustic problems in the libraries can be divided into five categories: sounds spreading from children and youth's sections to other areas, sounds spreading from floor to floor, background noise level, reverberation and sound insulation. These properties were measured in each library and the results were compared to recommendations and the experiences of the library staff. In addition, a listening test was conducted to investigate the staff's personal preferences on different acoustic environments.
The vast majority of the results supported the existence of the problems above, for they differed from the recommendations or only barely fulfilled them. The listening test in turn confirmed that people prefer different acoustic environments in a library. However, the baseline for the solutions was to remove all the problems observed.
The acoustics can be improved by controlling the reverberation and the spreading of sound. The libraries should add sound absorbing materials on for example walls and ceilings, place obstacles restricting the spreading of sound between sections, and raise the background noise level. Thick and well sealed structures or foldable walls would in turn be needed in the rooms with sound insulation requirements. The implementation of the solutions has to be planned for each library specifically since their facilities vary.
All in all, the acoustics has not been properly taken into account in libraries. It affects the problems in the soundscapes and attention should be paid in designing it. A big change is indeed needed in the attitude: acoustics is an important part of the usability of a library and it should be a part of both new construction projects and renovations.

Keywords: acoustic design, acoustics, library, reverberation, sound insulation, soundscape, speech intelligibility, spreading attenuation, STI

Preface

First I would like to thank my supervisor, Prof. Tapio Lokki, for all the support and advice I got. He helped me with clarifying my own thoughts as well as gave me insight on the content of the work. After every meeting I felt I knew what I was going to do next. Thank you also for arranging the setup I needed for my measurements, along with Ilkka Huhtakallio.

For the thesis opportunity I would like to thank Harri Sahavirta and the whole team working for the project Changing Soundscape of Communal Libraries. Thank you Meri Kytö for giving me a completely different point of view on sounds and listening. That really enriched my work.

During the measurements and writing process a huge help has been my dear partner James. He was willing to spend hours in libraries following my orders, listen to all the problems and worries, and read through and comment everything I asked for. Without him the process would have been if not impossible then at least significantly more stressful.

Big thanks belong also to all the people who gave me advice along the way, was it then technical, writing related or more general. The mental support of you fellow thesis writers – Vilja, Otto, Kati – was often relieving. Finally, thank you for reading through and commenting the final report: mom, Vilja, Otto and James. Your insight let me take a step back from the work I already know too well and make it even better.

Now, all is done and it is time to move on.

Otaniemi, 10.10.2016

Minna M. Santaholma

Contents

Symbols and abbreviations

Symbols

A	absorption area
α	absorption coefficient or weighting factor
β	redundancy factor
c	speed of sound in air
DL_2	rate of spatial decay of sound pressure level per distance doubling
f	frequency
f_m	modulation frequency
I_i	incident sound intensity
I_r	reflected sound intensity
I_t	transmitted sound intensity
k	wave number or index
k_dir	directivity of a sound source
λ	wavelength
L_p	sound pressure level
L_W	sound power level
m	modulation reduction factor
Ω	solid angle
p	pressure
$\hat{p}$	pressure, amplitude of a sinusoidal wave
p_0	reference pressure
p_{tot}	total pressure
ρ	air density
r	distance
r_D	radius of distraction
R	sound reduction index, in laboratory
R'	apparent sound reduction index, in situ
R_w	weighted sound reduction index, single number, in laboratory
R'_w	weighted apparent sound reduction index, single number, in situ
S	surface area
SNR’	Apparent Signal-to-Noise Ratio
t	time
τ	transmission coefficient
T	reverberation time
T_{20}	reverberation time, assessed from decay curve between values -5 dB and -25 dB
T_{30}	reverberation time, assessed from decay curve between values -5 dB and -35 dB
V	room volume
W	sound power
x	location variable

Abbreviations

AI	Articulation Index
CVC	Consonant-Vocal-Consonant
EDT	Early Decay Time, reverberation time assessed between values 0 dB and -10 dB
HVAC	Heating, Ventilation and Air Conditioning
IR	Impulse Response
MTF	Modulation Transfer Function
MTI	Modulation Transfer Index
PB	Phonetically Balanced
RASTI	RApid Speech Transmission Index
RMS	Root-Mean-Square
S	Source
SII	Speech Intelligibility Index
SNR	Signal-to-Noise Ratio
SPL	Sound Pressure Level
SRT	Speech Reception Threshold
STI	Speech Transmission Index
STIPA	Speech Transmission Index for Public Address systems
STITEL	Speech Transmission Index for TELecommunication systems
TI	Transmission index

1 Introduction

Communal libraries, as well as academic ones, have been under a lot of change during a couple of previous decades [1, 2, 3, 4]. The ways people use libraries and their services have broadened, and it is not all about books and silent reading any more. Libraries are also used for group work, meeting people, spending time with friends and organising events, just to name a few examples.

The variety of sounds in a library has been changing along with the services. Many of the newer library activities involve talking and making other sounds that did not exist in the space before. However, this sonic change has often been a by-product that has not been consciously thought of. As a result, even if the libraries were designed for accommodating the sounds before, that might not be the case now. If the library facilities are not adapted to the new louder sonic environment, sonic and acoustic problems can emerge. [1, 5]

In addition to the services and their sounds changing, people have different attitudes and expectations for libraries. At the same time when some people love the traditional silence, there are other people who want to hear the sounds of life. People's objectives for the visit may also vary significantly: some want to read news and discuss them with a friend, others need the silence they might not get anywhere else. [1, 5]

The contradictory needs together with the sonic and acoustic problems mentioned above have been evident in customer feedback. The issues remain the same in libraries across Finland, as was found in the survey in [1]. As a response, Helsinki City Library decided to start a national research project called Changing Soundscape of Communal Libraries (Finnish: Yleisten kirjastojen muuttuva äänimaisema) to find out what is expected and needed from the soundscape, the collection of sounds in a space, in a modern library. The objectives of the project were to produce new knowledge and to give tools for designing and controlling the soundscape. This project was very important to the staff members who had long been hoping for help with these issues.

The project was multidisciplinary and looked into all the different aspects of changing soundscape mentioned above. It combined soundscape research, acoustic measurements and human behaviour making it a unique research topic that did not seem to have been investigated before. During the year 2016 in five libraries four separate studies were conducted: current and ideal soundscapes were investigated with the library staff, acoustics in the facilities was measured and improved, customer needs were mapped with a survey, and the possibilities to affect the customer behaviour and expectations were explored.

This master's thesis is the acoustics part of the project. The aim is to quantify the acoustic problems found during the pre-survey [1] and the soundscape investigation, compare the results to guidelines, and suggest ways to improve the situation. The effect of the improvements is tested afterwards by repeating the measurements, but that is out of the scope of this thesis. To the best knowledge of the author similar studies in libraries have not been conducted before.

In addition to the objective measurements, a subjective comparison of the libraries is done using a listening test. The objective of the test is to compare the measured libraries and to define the order of preference of the acoustics in them. Eventually, the results from this thesis are generalised and included in the design guidelines produced by the project.

This thesis is organised as follows. In chapter 2 the context and theoretical background for this thesis are explained. After that, in chapter 3, the measurement processes and the five libraries are presented, followed by the results in chapter 4. Chapter 5 is dedicated to the subjective comparison of libraries and the implementation of the listening test. Both objective and subjective results are combined in chapter 6 as suggested improvements. Finally the conclusions are presented in chapter 7.

2 Theoretical background

The purpose of this chapter is to present the context of this thesis and to go through all the necessary theory for understanding the measurements and their results. Since changing soundscape is the key of this project, and foreign to many, it is the first theme to be introduced. After that the properties of modern libraries and sounds in them are gone through to give an idea of the environment measured. In the third section, all the acoustic terms and quantities used in the measurements are briefly explained. Lastly, the requirements for the acoustics in a library are listed.

2.1 Soundscape research

Soundscape is the collection of all kinds of sounds we hear in a space. For example, at home you can hear the fridge humming, mobile phone announcing a new message and birds singing outside. A soundscape also includes the listener and her interpretation of the sounds: how one listens or does not listen to the sounds, how one produces or avoids producing sound oneself, how sounds are understood and noticed. [6] It is a sonic environment being listened to subjectively [7].

The sounds can be of several types, some of which require reacting and others not. One sound can be the keynote sound that dominates the soundscape. Sometimes the sounds cannot be separated to individual sources resulting in a lo-fi soundscape, opposing a hi-fi soundscape where sound sources are easy to identify and name. [7]

Acoustic space is a key term that can have several definitions due to the multidisciplinary approach one can take on sound. In short, it is the space where a soundscape can form. It can be the area in which an individual sound can be heard or the sonic environment formed by a listener. In cities different kinds of sound sources are producing sound so densely that acoustic spaces overlap. In a city apartment, for instance, the sounds from the outside, e.g. traffic or neighbours, can often be heard, and vice versa. [6]

Soundscape research investigates first of all the sounds that make the soundscape. In addition to that it also looks into how the sounds are listened to, and how they are related to cultural aspects. The research subjects can include: sonic identity of a mountain village, radio in the soundscape of a workplace, acoustic communication, or using power through soundscape. The last one is in practice about affecting the behaviour of people by designing the soundscape in a certain way. An example in many cities is to use classical music to make it less pleasant for the youth to gather around shopping centres and similar public areas. [7]

Soundscape research is used in this project to find out what the soundscapes in different libraries are now and what the ideal soundscape would be. Together with this thesis and the other studies in the project, the soundscape of libraries is not only analysed but also developed and guided. Investigating the soundscape, along with directly asking the library staff, reveals the sonic problems in each library. Some of these problems are then chosen to be further looked into with acoustic measurements.

2.2 Library as a space

Libraries have existed for a long time: their original function as preserving all possible written information dates back several thousands of years. Maybe the most famous public library was the library of Alexandria, founded around 300 BCE, where the scholarly qualified were allowed to go and read [8]. From this we have come quite far. In this section the properties and services of the modern library are briefly presented, along with some thoughts on the sounds in libraries.

2.2.1 Modern library

The type of communal library network that Finland has now, started forming at the end of the 19th century. The inspiration for libraries that would be open and free for everyone came from the Public Library Movement in the United States. The properties were owned and maintained by public authorities. [9]

Traditionally the objective of libraries has been to educate people. High class fiction, non-fiction and daily news were an essential part of giving the possibility for people to learn and become civilised. Nowadays, the services a library offers can vary and sometimes even be completely unrelated to books or other recorded media. During the last couple of decades electronic materials have changed the need for books and broadened the material that can be offered, also in the form of equipment. In some areas library is the only place for children to come and spend the afternoon in without the need for buying anything. [1, 2]

Libraries vary in size and location. The people using the library affect the services that are needed and used, and libraries have been responding to these needs. More research on this has been done on academic libraries [3, 4], but the phenomenon is the same in communal ones [2].

There are still some spaces that appear in most libraries, regardless the size: main hall with adult fiction and non-fiction, children's area, reading room, an event space/area and a customer service area. Less quiet reading places have been spread around the library to offer nice spots to read. Bigger libraries can also offer rooms for group work or individual work, listening and playing rooms for music, and computer rooms. Youth and children's sections might have board games or game consoles. Some libraries have even taken in 3D-printers and other tools for creation, and organise workshop sessions where this equipment can be used. Living room type areas and small cafés make the library feel more like home or a place to spend time in with friends, chatting about the current news read from the day's newspaper. Some people come to seek a quiet place to study or to borrow a computer.

People come to do very different things in a communal library. This also means they have different objectives for their visit and varying expectations of what the soundscape or the acoustics should be. Compared to academic libraries where students and staff study and have a relatively unified goal, communal libraries have the challenge of a very heterogeneous public wanting and needing different services. [1]

2.2.2 Sounds in libraries

The sounds in libraries have changed along with the changes in services. The voice control in public areas is also different to what it used to be, resulting in not everything being forbidden in libraries anymore. The sounds of life are now allowed to be heard. [1]

At the same time that there are customers who love hearing the sounds of life, there are others who appreciate the traditional silence demanded in the whole library. For some the library is the only place where the calm silence can be found, and that is something everyone needs every now and then [5]. Consequently, the customer feedback can be very conflicting [1]. That, in turn, makes it difficult to design the spaces so that everyone would find a suitable spot, both functionally and soundwise.

All the services and areas in a library have their characteristic sounds. To accomodate those sounds a suitable sonic environment is required for comfort and functionality. For example, in the customer service area it is important that the staff member and the customer hear each other well but the conversation is not audible elsewhere. Otherwise, in children's section children like to talk and play, and the reading room should be quiet and the sounds from other people in the room really faint to make learning possible. [10] In a building with many areas and rooms also the effect of the other areas has to be taken into account, since they are not always separated by sound insulating structures. The space should be designed so that all these possible sonic needs can be satisfied at the same time.

Even when a space seems to have a good soundscape and acoustic properties, it might not suit everyone. People are different and have different needs for e.g. studying. It has been found [11] that students choose their studying area based on their personal preferences on the background noise, and the acceptable levels obtained from the tests differed clearly.

The modern society relies more on people finding their intrinsic self-regulation than placing orders and prohibitions. In libraries the shushing environment has been replaced with the opposite: not interrupting the disturbance before it is absolutely necessary. [1] This makes controlling some of the sounds difficult for the staff and other customers, since it can feel unacceptable to go and tell someone else's children or an adult to be quiet. Some other ways to orchestrate, not control, the sound are needed [5]. The attitude towards intervening can of course vary from library to library.

Shaping the sonic environment requires careful design, which is well described in [5]. In the case of existing libraries it is necessary to investigate the sources of sound, the behaviour and needs of people and how the space affects the soundscape. The first two have been taken care of in their respective studies in this project whilst in this thesis the acoustics of the space is the main subject.

The research is done by measuring the relevant acoustic properties of the participant libraries, based on the problems pronounced by the libraries themselves. The common problems that were brought up involved the facilities being too reverberant, silent rooms being disturbed by louder ones, and sound being carried too far, especially from children's or youth's sections. In this thesis, to quantify these problems, reverberation, sound insulation and sound attenuation are measured. Since speech is the most distracting type of signal [10], speech intelligibility is also analysed from the measurements. The theory behind these quantities is presented in the following section.

2.3 Room and building acoustics

This section goes through the basics of sound and its behaviour in rooms and between rooms. There are numerous different quantities that can be measured and calculated to describe a space; the ones relevant to this thesis are presented below. Reverberation, attenuation and speech transmission quantify a room inside its boundaries whilst sound insulation includes the effect of sound on the adjacent spaces.

2.3.1 Basics of sound

Sound is a wave that travels in a medium, such as air, water or the steel in train tracks. More specifically, it is a longitudinal wave where the motion of particles happens back and forth along the propagation direction, creating pressure variations. This wave can be written as a function of pressure p, location x and time t. For a given frequency f in one dimension the equation is

$$p(t) = \hat{p}(t) sin(2\pi f t \pm kx), \tag{1}$$

where $\hat{p}$ is the amplitude of the wave that usually decreases in time, and k is the wave number. From the frequency and the speed of sound c the wavelength λ of the wave can be solved: $\lambda = c/f$. In air in room temperature, the speed of sound is around 340 m/s. An example of the nature of a sound wave is presented in Fig. 1.

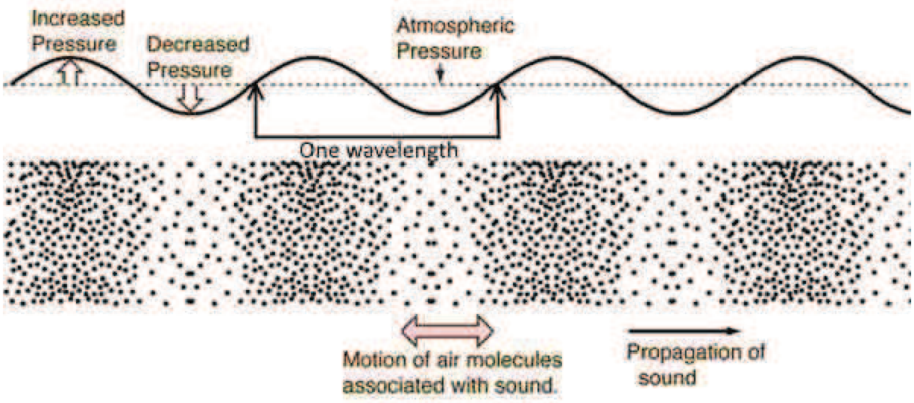


Figure 1 – One dimensional sound wave at one frequency. Adapted from [12].

Many sounds consist of several different frequencies instead of only one. This kind of wave can simply be described as the sum of all individual components. The contents of this signal can be presented in a graph called frequency spectrum, where e.g. the pressure is marked for each frequency component. An example can be found in Fig. 2.

It is often sufficient to give the pressure value for a specified frequency range instead of all individual frequencies. The human audible range is from 20 Hz to 20 000 Hz and it can be divided into 10 octave or 30 1/3-octave bands. An octave means doubling of the frequency. The width of the frequency range is 70 % of the centre frequency for an octave band and 23 % for a 1/3-octave band. [13] An example sound spectrum is shown at both octave and 1/3-octave bands in Fig. 3.

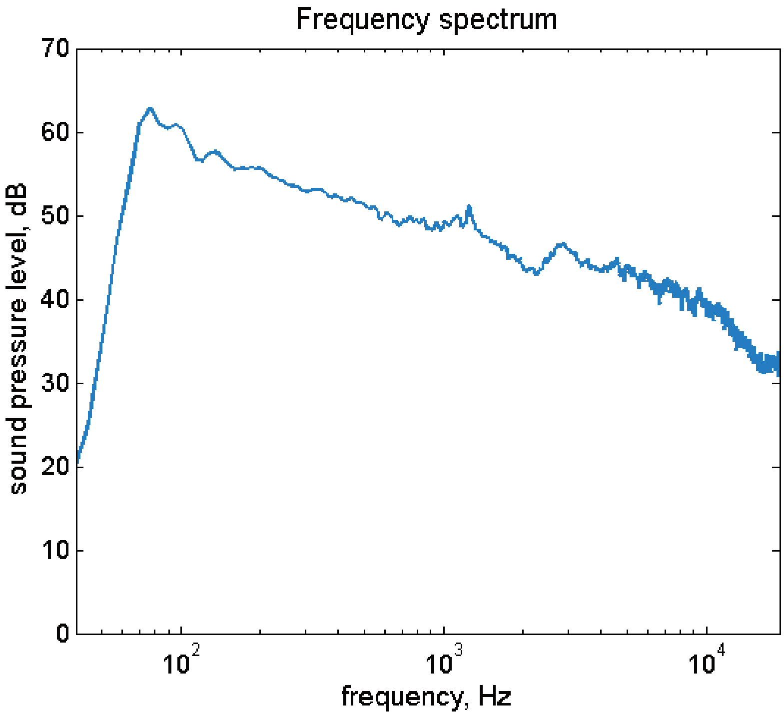
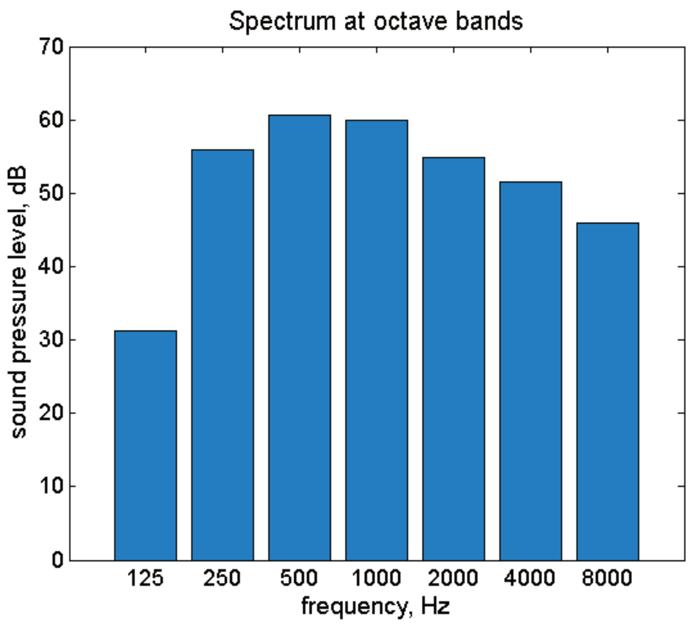


Figure 2 – Example of a frequency spectrum obtained from a measurement in front of a loudspeaker. The input signal was pink noise.

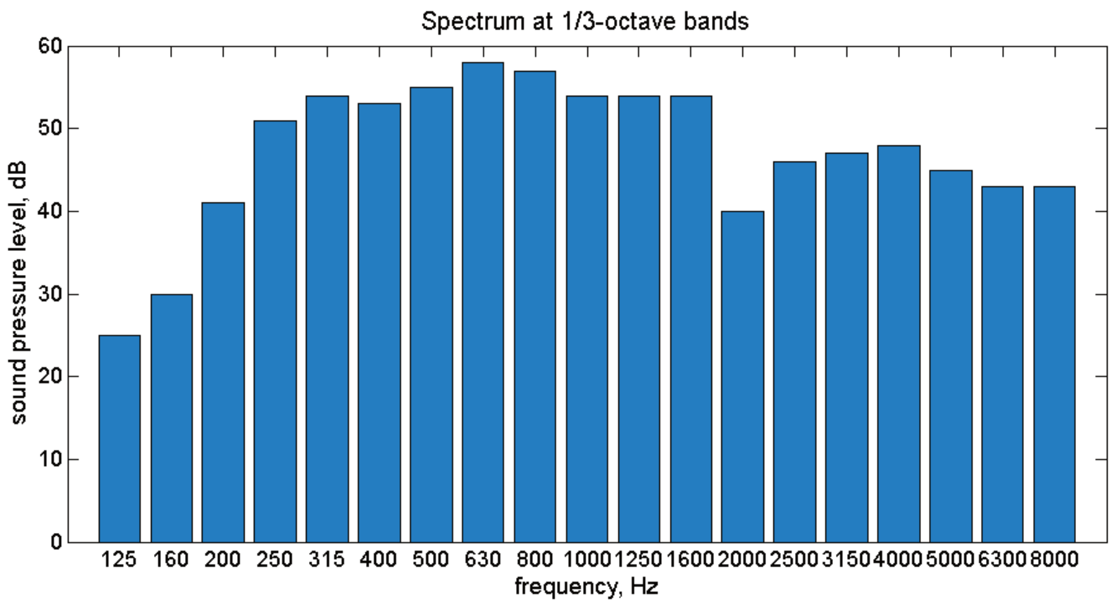
Sound level is often expressed in decibels that compare two quantities. The reason for this is that the pressure variations caused by a sound wave are small compared to the atmospheric pressure, but the pressure at the threshold of pain is approximately 10 million times the pressure at the hearing threshold. The two quantities to be compared can be chosen freely as long as they have the same unit. For absolute values the reference is fixed and chosen so that 0 dB represents the threshold of our hearing at 1 kHz. In terms of pressure, a quantity called sound pressure level (SPL) can be calculated, and the equation is as follows:

$$L_{\mathrm{p}} = 10log(\frac{p^2}{p_0^2}) = 20log(\frac{p}{p_0}). \tag{2}$$

L_{p} is the symbol for SPL and p_0 is now the reference for pressure with a value of 20 μPa. The pressure p is the root-mean-square (RMS) value of the sound. As said above, 0 dB corresponds to the hearing threshold, whereas 140 dB is the threshold of pain. Different SPLs with example sources are demonstrated in Fig. 4. A 3 dB increase or decrease in SPL is perceived as double or half the loudness, respectively.



(a)



(b)

Figure 3 – A sound spectrum presented at both a) octave and b) 1/3-octave bands at a frequency range 125-8000 Hz. The signal was average child speech.

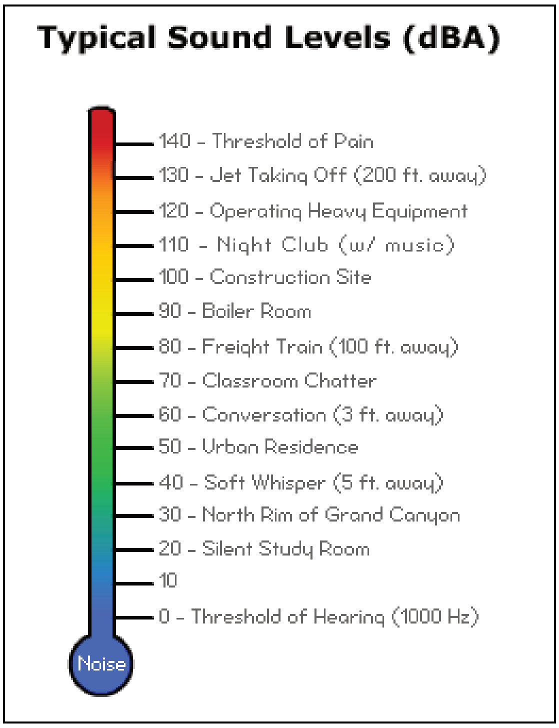


Figure 4 – Examples of different sound pressure levels in dB and their sources. Reprinted from [14].

In case of multiple sources or the need to average for example measurement signals, sound pressures need to be summed together to get one common SPL. If the sources produce sound that is incoherent, i.e. the phases of the soundwaves do not correlate, a squared sum of the individual pressures is taken [15]:

$$p_{\mathrm{tot}}^2 = p_1^2 + p_2^2 + \dots \tag{3}$$

For p_{tot} the SPL can then be calculated using Eq. (2).

This kind of SPL calculated directly from the sound pressure does not always correspond to what humans hear. The reason is the sensitivity of our hearing and different hearing thresholds at different frequencies. For instance, outside the human audible range there is infrasound and ultrasound below and above it, respectively. The audible range also varies between individuals and usually narrows down from the higher end while aging [16, p. 80]. In addition, we are less sensitive to low frequencies than for the frequencies found in speech. This can be seen in the set of equal loudness contours for pure single frequency tones obtained by Fletcher and Munson [17]. These contours are shown in Fig. 5.

Based on the equal loudness contours, weighting curves have been developed to take into account the varying sensitivities of an average listener. The weighting curves give less weight to the frequencies humans are insensitive to and more to the ones that are heard even at a low SPL. This way they shape the spectrum of the sound. Mathematically this means multiplying the spectra of the sound and the weight with each other.

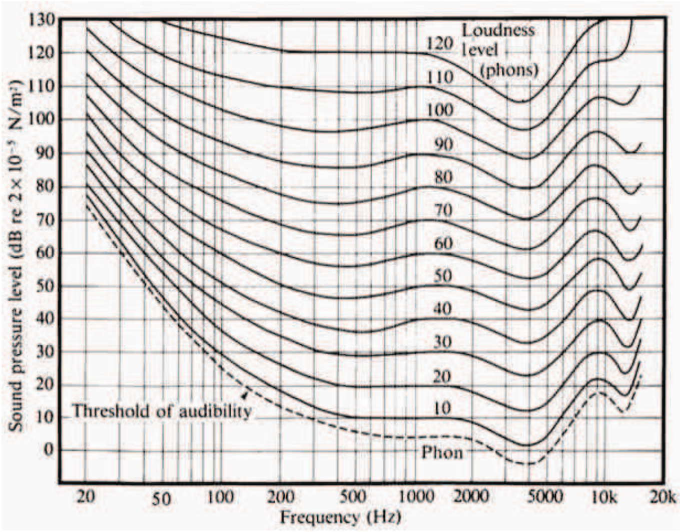


Figure 5 – Equal loudness contours obtained by Fletcher and Munson and now defined by the standard ISO 226:2003. Phon as a unit describes the loudness level of a pure tone. While following one contour across the frequency range the sensation of loudness remains the same. Reprinted from [16, p. 107].

The most widely used of the weighting curves is A-weighting that was already mentioned in Fig. 4 in the unit dBA [15, 16]. It resembles the equal loudness contours at low SPLs. Another weighting curve sometimes used is C-weighting. It is more suitable for higher SPLs since its spectrum is relatively flat and it thus resembles the equal loudness contours at those levels. The spectra of these two weights are shown in Fig. 6. Other curves also exist but they are rarely used [15].

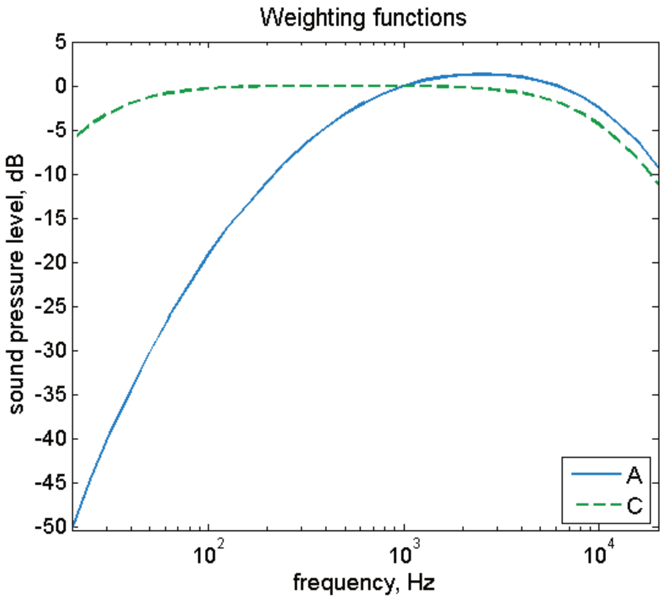


Figure 6 – A- and C-weighting curves, or functions, for shaping the sound spectrum to correspond better to the sensitivity of human hearing. The values are taken from [15].

2.3.2 Reverberation and attenuation

In the previous subsection the environment where the sound is propagating or the distance between the listener and the source were not taken into account. In reality, these two affect the sound heard and the soundscape experienced.

When a source radiates sound equally to all directions in a free space the source is said to be in a free field. In a free field there are no reflections, which means that the only sound a listener can hear is the direct sound from the source. The SPL decreases over distance as the sound power W emitted by the source is distributed over a sphere surface of $4\pi r^2$, where r is now the distance from the source. When the distance doubles, the SPL is reduced by 6 dB. In reality, this kind of situation can approximately be achieved outdoors in an open area with soft ground or in an anechoic chamber. [16, p. 101-102, 525-526]

In rooms the situation is different than in a free field. The room boundaries and all the objects in the room act as reflectors, diffusers or absorbers to the sound. The typical result is a series of reflections from varying surfaces, reaching the listener after hearing the direct sound from the source. At first, there are a couple of reflections that reach the listener 50 to 80 ms after the direct sound. These are called early reflections and they reinforce the direct sound, despite being attenuated. The following reflections attenuate even more and arrive closer and closer to each other, eventually merging into so called reverberant sound. [16, p. 525-528] If the original sound was only an impulse, an impulse response (IR) would be obtained as pressure variation in time (Fig. 7). The IR can be presented in decibel scale, and this kind of decay is illustrated in Fig. 8.

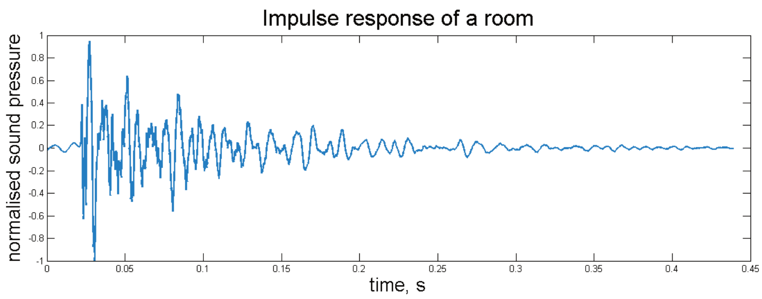


Figure 7 – An example impulse response in a room.

The decay rate in Fig. 8 can be formed into a single number that describes the reverberation of the room. This number is called reverberation time and it tells the time it takes from the sound to decrease 60 dB in sound pressure level. The most important part of the decay curve is the start of the reverberation [15]. That is why the reverberation time is usually analysed from the time it takes from the sound to attenuate from -5 dB to -25 dB, when the original SPL is 0 dB. This time is then multiplied by 3 and it is denoted by T_{20}. It is also possible to use -35 dB as the lower limit, in which case the time is multiplied by 2 and the symbol is T_{30}. While assessing speech transmission properties, the early decay time (EDT) assessed between 0 dB and -10 dB, multiplied by 6, describes the decay in early reflections that affect the speech intelligibility. Fig. 9 shows a visualisation of estimating these different times from the decay.

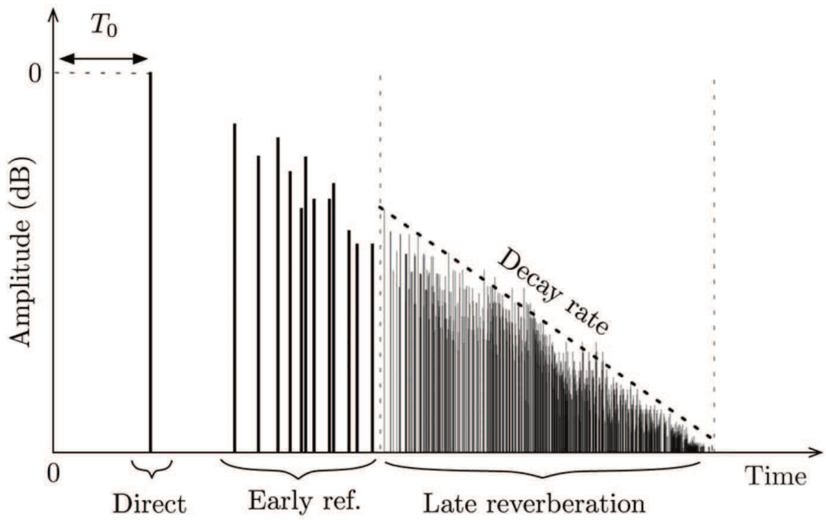


Figure 8 – Reverberation in an ordinary room caused by an impulse. After the direct sound, there are a couple of early reflections after which the dense late reverberation starts. Reprinted from [18].

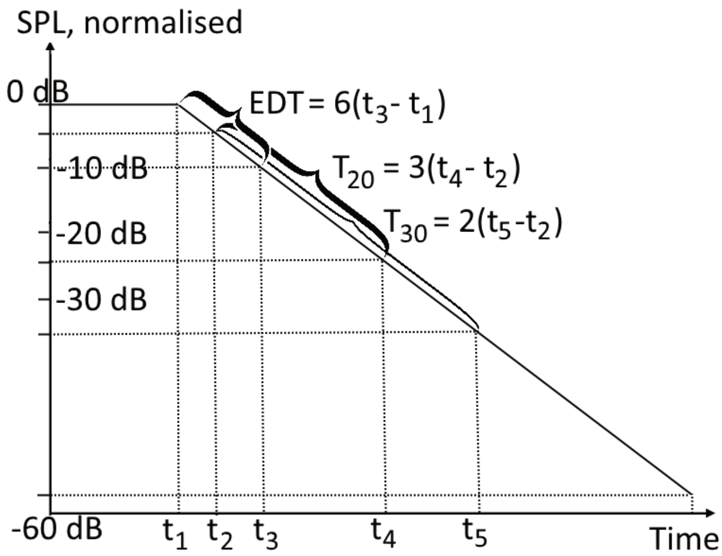


Figure 9 – A visualisation of estimating the reverberation time from a decay curve. In this example the curve is a straight line and the times are the same, but in reality the slope of the curve can vary and thus give different results depending on the attenuation range used.

In each room, the reflection pattern and the reverberation is unique and can be rather complicated. Reverberation time is still a relatively good indicator of the liveliness of the room. Examples of reverberation times in different kinds of spaces are listed in Table 1. If the reverberation characteristics of the room are to be studied further, there are numerous quantities, mostly for performance spaces, that can be defined from the decay. [16, p. 529, 534-540]

Table 1 – Examples of reverberation times in different spaces, at 500 Hz octave band. Adapted from [13].

Reverberation time, [s]	Space
> 5	Stone church, empty
2...3	Big hall, no absorption
1.8...2.2	Concert hall
1.5	Unfurnished bedroom
1.0...1.2	Theatre, auditorium
0.5...0.8	Well designed classroom
0.5	Furnished bedroom
0.3...0.8	Movie theatre, depending on volume
0.2...0.3	Sound control room, depending on volume

Reverberation time is affected by the surface materials in a room. The choice and placing of the materials can for example improve the quality of an auditorium or make an office a pleasant and quiet place to work. Materials have different absorption coefficients, which allows tuning the reverberation properties. [10]

The absorption coefficient α of a surface tells how much sound the material absorbs. It is the ratio between the sound intensity that did not reflect back and the incident sound intensity [15]. Thus, the value can vary between 0 and 1. As an equation, it is defined as:

$$\alpha = \frac{I_\mathrm{i} - I_\mathrm{r}}{I_\mathrm{i}}, \tag{4}$$

where I_i is the incident sound intensity and I_r is the reflected sound intensity. The coefficient is a function of frequency, and the higher the values are the better the absorption.

The reverberation time T can be estimated if the volume V and the absorption area A of the room are known. Respectively the absorption area can be calculated if the reverberation time has been measured. The absorption area is the area of all the surfaces in the room multiplied by their absorption coefficients, and it affects the rate of sound energy absorbed in a room. Sabine's formula combines these quantities into

$$T = 0.16\frac{V}{A}. \tag{5}$$

Good absorption materials that really affect the reverberation let almost all of the incident sound enter the material. Inside the material layer, part of the particle movement in the sound wave is turned into heat. Often these materials are very porous with open pores, such as rockwool, or have tuned resonators in the structure. [15]

Since some of the sound can get through the absorption layer, it matters how thick the layer is and what has been put behind it. Absorption is the most efficient when the layer coincides with the maximum of the particle velocity in the soundwave. If there is a reflective surface behind the layer, the particle velocity is zero on the surface and the maximum is at a quarter of a wavelength's distance from the reflection spot. As a result, long wavelengths require thicker layers or positioning of the layer. [10, 13, 15] The situation is demonstrated in Fig. 10 and in Fig. 11.

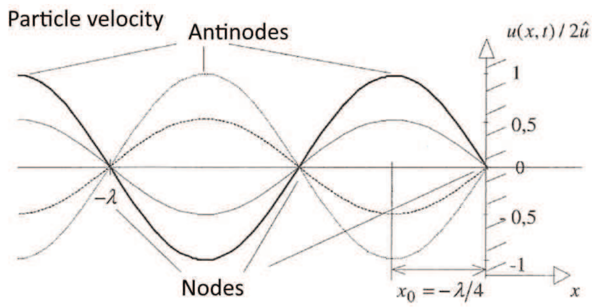
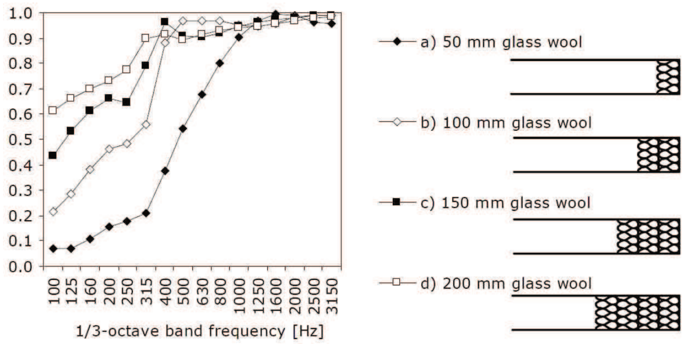
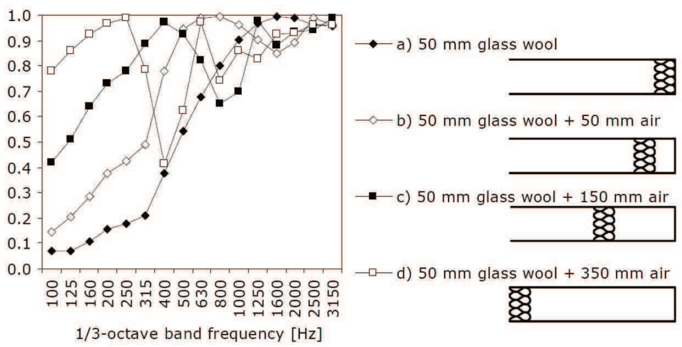


Figure 10 – Particle velocity after a reflection of a plane wave at a normal incident angle. The reflective surface is on the right. Adapted from [15].



(a)



(b)

Figure 11 – Effect of a) thickness and b) placing of a glass wool layer on the absorption coefficient, on a reflective surface. The dips at certain frequencies in b) are the result of the absorption being placed at the particle velocity minimum of that frequency. Wool density was 18 $\mathrm{kg/m^3}$ and the measurements were done at normal incident angle. Reprinted from [15].

The absorption area defines the attenuation of sound in a room. If the room is of a relatively simple geometry and quite small, the SPL for a source with a sound power level L_W can be calculated from

$$L_\mathrm{p} = L_\mathrm{W} + 10log(\frac{k_\mathrm{dir}}{\Omega r^2} + \frac{4}{A}), \tag{6}$$

where k_{dir} is the directivity of the source and Ω the solid angle where the source is radiating. Solid angle 4π means radiation to all directions, 2π to half the space etc. The attenuation introduced by the room is the term $4/A$, which is independent of the distance and cannot result in a larger attenuation than in a free field. If the space has a complex geometry, is highly absorptive or large, the sound can attenuate significantly more and be dependent on the distance from the source. A quantity called rate of spatial decay of SPL per distance doubling DL_2 can then be measured. It tells how many decibels the sound gets attenuated every time the distance from the source is doubled. [15] Fig. 12 shows a few examples on the subject.

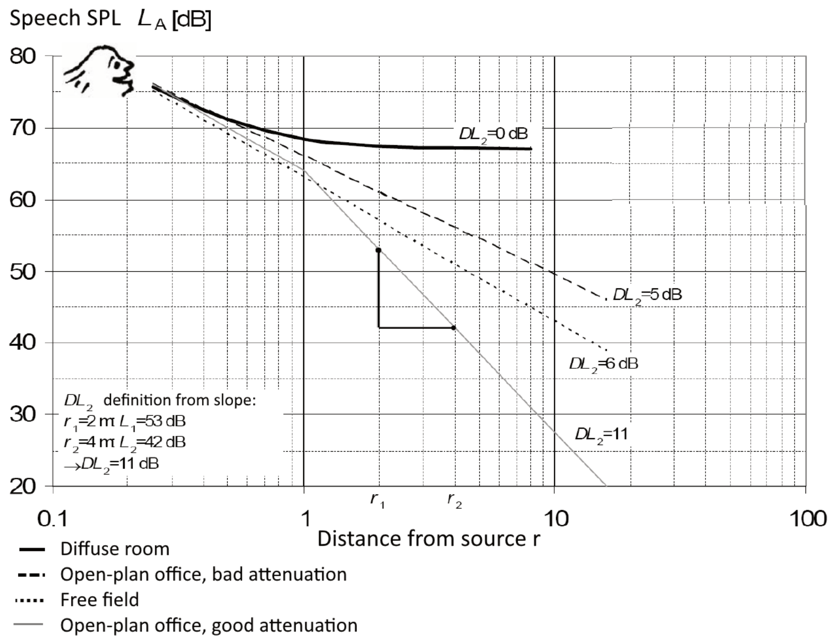


Figure 12 – Rate of spatial decay per distance doubling in different conditions. The diffuse room curve corresponds to Eq. (6) with an absorption area of 10 m^2. Adapted from [13].

2.3.3 Speech intelligibility

Speech intelligibility in a room depends on many factors. Reverberation time introduced in the previous subsection is one of them, but the level difference between background noise and speech, the distance from the speaker and the direction the speaker is facing are also essential [13].

Obviously the level at which the speaker is speaking affects the level difference to background noise. This difference is also called Signal-to-Noise Ratio (SNR). In different situations the speech level can also be higher or lower depending on what is needed. Examples of A-weighted SPLs at different vocal efforts are presented in Table 2 for men, women and children.

Table 2 – A-weighted speech levels in dB for women, men and children at different vocal efforts. Adapted from [19].

	Casual	Normal	Raised	Loud	Shouted
Female	50	55	63	71	82
Male	52	58	65	76	89
Child	53	58	65	74	82

Speech is a wideband signal that contains information mainly in the frequency range of 100-10 000 Hz [13]. Men, women and children have their own base tone ranges at frequencies 100-200 Hz, 200-400 Hz and around 500 Hz, respectively. The average speech spectra for them differs from each other, which can be seen in Fig. 13. These spectra also move towards higher frequencies when the speech level is raised [13].

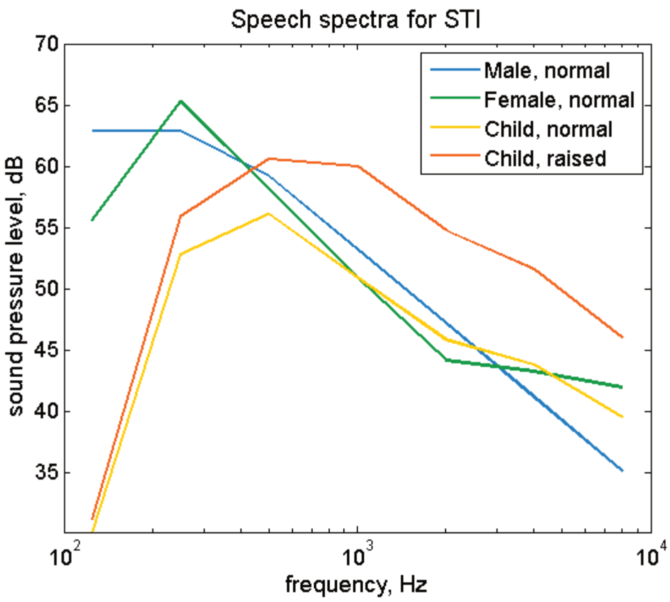
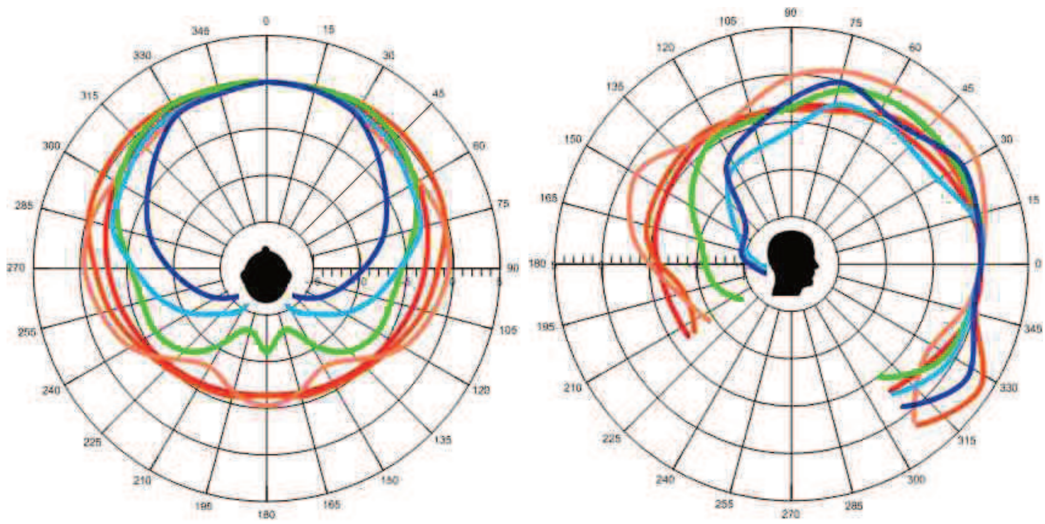


Figure 13 – Average speech spectrum for men, women and children at normal vocal effort. As an example of the effect of raising one's voice the spectrum for a child at raised vocal effort is shown. The spectra for men and women are from standard ISO 60268-16 [20] at A-weighted SPL of 60 dB@1 m, and the spectra for children was adapted from [19]. The 125 Hz value for women has been taken from [21].

The spectra and SPLs shown have been obtained at 1 m in front of the speaker. The result would not be the same for example behind or above the speaker. Our head is an obstacle around which the sound has to travel, and at high frequencies it has a significant effect on the frequency content and the SPL level heard [13]. The frequency dependence in the directivity is illustrated in Fig. 14. From the plot it can be seen that the frequency content, and level, of speech changes depending on where the listener is. This has an effect on speech intelligibility. At low frequencies, the head is smaller than the wavelength and the mouth looks like a point source, letting the sound radiate to all directions. When the frequency is increased, the directivity becomes more prominent.



(a) (b)

Figure 14 – Directivity of a speaker at different frequencies, in a) the horizontal plane and in b) the vertical plane. Each colour represents one frequency starting from 160 Hz (red) to 8 kHz (blue). Reprinted from [22].

Speech intelligibility can be quantified with the Speech Transmission Index (STI). It is a quantity that roughly estimates the quality of the speech transmission of syllables [13]. The value varies in the range of 0.00-1.00 where a higher value means better intelligibility, 1.00 being perfect. The desired value depends on the use of the space. Classrooms need very high and private office rooms very low STI values, resulting in good speech intelligibility or speech privacy, respectively.

Other methods, such as the Speech Intelligibility Index (SII, previously Articulation Index, AI) and different word or phonetics tests can be used, but the STI is a simple method to implement. It also includes relatively complex modelling of the hearing process. However, there are some limitations to the method if e.g. the frequency response of the room varies a lot. [20] The STI, as its inspiration AI, can be calculated from acoustical and physical measurements and does not need complicated laboratory tests [23, 24].

The STI is based on the work of Houtgast and Steeneken that started in 1971, presented in [23]. The idea is to estimate how the path that the sound takes from the speaker to the listener affects the speech received, at octave bands 125-8000 Hz. The acoustics of the space filters, shapes and smears the speech signal.

The STI method uses Modulation Transfer Functions (MTF) to estimate the smearing caused by the room at each octave band [25]. A speech signal consists of phonemes, sounds representing letters and letter combinations, and as the speaker moves from one phoneme to another the speech varies, i.e. modulates. The reverberation in rooms tends to cause the quickest modulations to disappear before they reach the listener. The frequencies of modulation can be estimated from the envelope of the speech signal, i.e. the general shape of it. The range used in the STI is 0.63-12.5 Hz. Background noise level in turn affects the SNR and reduces the depth of the modulation. These two distinct effects of the room are illustrated in Fig. 15.

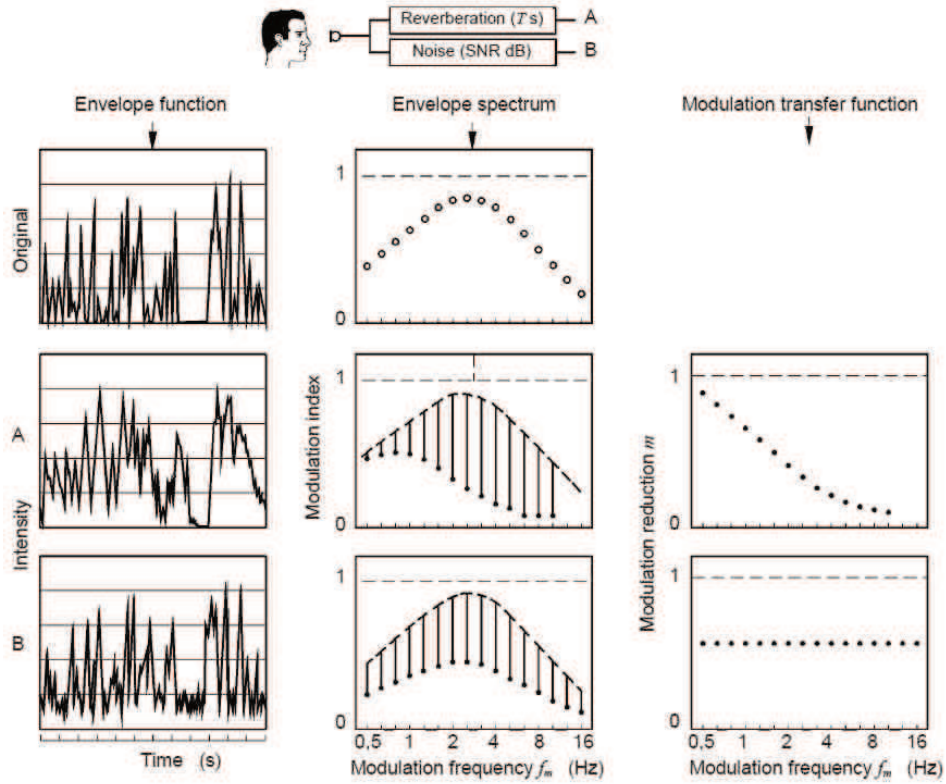


Figure 15 – Illustration of the effects of reverberation and SNR on speech in a room on the path from the speaker to the listener. The envelope spectrum shows how much of slow and quick variations there are in the speech, and rows A and B demonstrate the effect of reverberation and noise to the content of that spectrum, respectively. Reprinted from [20].

The effects of both reverberation and SNR can be represented mathematically, forming an equation for modulation reduction index m [20, 25]:

$$m(f_m, k) = \frac{1}{\sqrt{1 + [\frac{2\pi f_m T_k}{13.8}]^2}} \frac{1}{1 + 10^{-SNR_k/10}}, \tag{7}$$

where f_m is the modulation frequency observed, and T_k and SNR_k are the reverberation time and SNR of one specific octave band k, respectively. The reverberation time is the EDT [15]. In the standard IEC 60268-16:2011 [20], 14 modulation frequencies are used: 0.63, 0.80, 1.00, 1.25, 1.60, 2.00, 2.50, 3.15, 4.00, 5.00, 6.30, 8.00, 10.0 and 12.5 Hz. The SNR is defined as the difference between the mean SPL levels of the signal and the background noise. As a result, a table of 7x14 values is obtained.

The MTFs do not represent the STI yet. To get there, the MTFs are converted to apparent SNRs (SNR'), limited between -15 dB and 15 dB, converted to Transmission Indices (TI) and Modulation Transfer Indices (MTI), finally ending at calculating the STI [20].

The SNR' is calculated with the following formula for each cell in the 7x14 table:

$$SNR' = 10log(\frac{m}{1-m}). \tag{8}$$

After limiting the values to the -15 dB...15 dB range a TI can be calculated for each combination of f_m and k:

$$TI_{f_m,k} = \frac{SNR'_{f_m,k} + 15}{30}. \tag{9}$$

MTI is an average of the TIs on a specific octave band:

$$MTI_k = \frac{1}{14}\sum_{m=1}^{14} TI_{f_m,k}, \tag{10}$$

from which the STI:

$$STI = \sum_{k=1}^{7} \alpha_k MTI_k - \sum_{k=1}^{6} \beta_k \sqrt{MTI_k \times MTI_{k+1}}. \tag{11}$$

The coefficients α_k and β_k are the weighting factors for octave band k and the redundancy factor between bands k and $k+1$, respectively. The weighting factors give more influence to the octave bands that are more crucial in speech, and the reduction factors take into account the interaction between adjacent octave bands through auditory masking. In auditory masking, part of the sound in octave band k masks some of the sound in octave band $k+1$, even if the frequency content did not overlap. [23]

The weighting and redundancy factors are gender specific and presented in Table 3. For child speech, the factors for a female speaker were used in this thesis, since no separate factors for children could be found and female speech spectrum is relatively close to the child's one.

Table 3 – The weighting and redundancy factors α and β for male and female speech. Reprinted from [20].

Octave band, [Hz]		**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Male	α	0.085	0.127	0.230	0.233	0.309	0.224	0.173
	β	0.085	0.078	0.065	0.011	0.047	0.095	-
Female	α	-	0.117	0.223	0.216	0.328	0.250	0.194
	β	-	0.099	0.066	0.062	0.025	0.076	-

This version of the STI with 98 modulation reduction indices is time consuming to measure, and simpler methods have been developed to reduce the time needed. These shorter versions include RASTI, STIPA and STITEL that also have their own specific uses. These are presented both in the standard [20] and the book of Houtgast and Steeneken [23].

As the STI is an objective quantity its values have to be connected to subjective measures. [26] These are called intelligibility measures, where the intelligibility score for certain types of words or sentences is calculated in different speech transmission conditions. In Fig. 16 the relation is presented between the STI and three intelligibility measures.

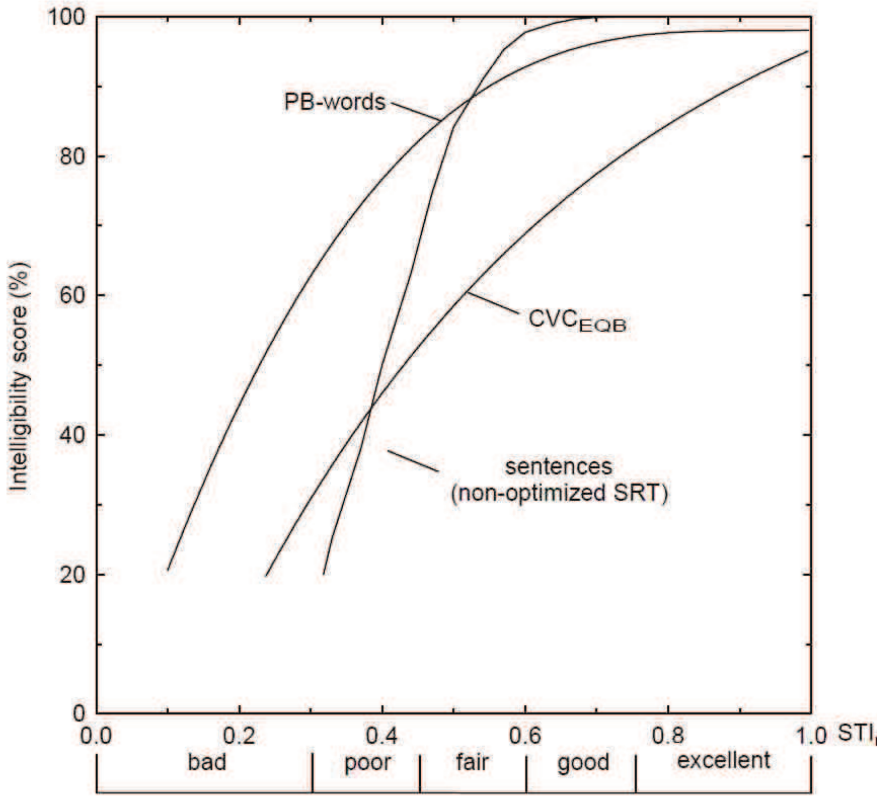


Figure 16 – STI values compared with intelligibility measures with nonsense CVC words (C=consonant, V=vowel), phonetically balanced (PB) words and sentences with non-optimised Speech Reception Threshold (SRT). The SRT is the smallest SNR for speech where the listener still understands the sentence. Reprinted from [23].

From the figure, it can be seen that when the STI goes below 0.60, the intelligibility score of sentences starts to decrease quickly. When it is less than 0.50 the annoyance and distraction caused by speech becomes significantly smaller. Radius of distraction, r_{D}, is defined as the distance from the source where this happens, and it is a common metrics used for evaluating the acoustics in open-plan offices. [10]

2.3.4 Sound insulation

As mentioned at the start of Sec. 2.3.1, sound does not propagate only in air but also in solid materials. In buildings this means that a sound produced in one room can be heard in the rooms adjacent to it, or even further away depending on the structures.

When the sound in a room hits a room boundary, e.g. a wall, some of the sound reflects back and the rest permeates the structure. Depending on the structure and its materials, some of the sound can also get through the boundary to the room adjacent to the first one.

This can happen through the structure between the rooms but also by ventilation ducts and other room boundaries. How much of the original incident sound is transmitted through the common structure can be calculated using its transmission coefficient τ:

$$I_{\mathrm{t}} = \tau I_{\mathrm{i}}, \tag{12}$$

where I_{t} is the transmitted sound intensity. The transmission is usually highly dependent on the frequency observed. [15]

The values of τ are small and vary over several orders of magnitude. This is why the capability of the structure to insulate airborne sound is expressed in decibels using sound reduction index R. [15] The decibel value tells how much the SPL in the receiving room is reduced from the SPL in the sending room. Using τ the index is defined as:

$$R = 10log(\frac{1}{\tau}). \tag{13}$$

The index R usually varies in the range 0...70 dB. The value depends greatly on the materials used and their placing in the structure. In every structure, there is always some absorption and transmission present. Examples of different combinations of these are demonstrated in Fig. 17.

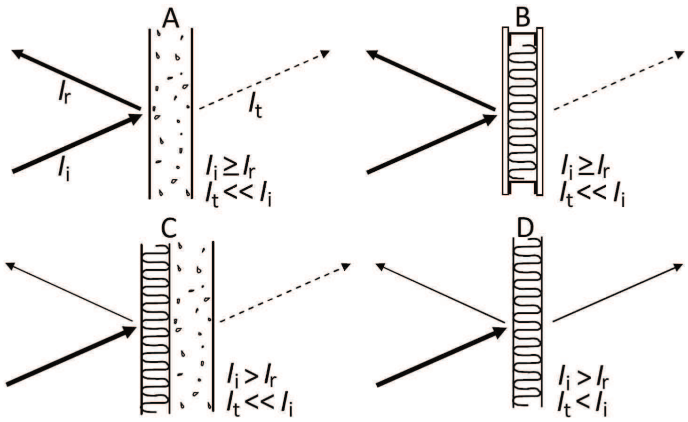


Figure 17 – Examples of the absorption and transmission happening in different kinds of structures. In A, there is a dense wall panel that has hard surfaces on both sides. In B, there are two thinner wall panels around absorption material. In C, the absorption material is placed on the wall of case A. In D, the absorption material is used alone. Reprinted from [15].

In the figure it can be seen that in case A the absorption coefficient is very low, and almost all the sound is reflected back. Transmission coefficient is between 20 and 80 dB depending on the surface mass. Case B is similar to A. The surfaces are reflective and the absorption material between the panels enhances the insulation properties of the structure. In case C, the absorption material is on the dense wall panel and reduces reflections significantly. Both absorption and insulation work efficiently in this structure. The example D shows that alone the absorption material is not insulating sound but letting most of it through. [15]

For real structures, the transmission coefficient is not known and the sound insulation is measured. The pressure method for doing so is presented in [13, 27]. In laboratories the structure under test is placed between two test rooms that are not connected to each other (Fig. 18). This way the other paths for the sound to propagate, i.e. flanking transmission (Fig. 19), can be avoided. One room is the sending room with a loudspeaker and the other one is the receiving room, measuring the sound that was transmitted through the structure. In situ, the separation of spaces is not possible and the measurements include the effect of flanking transmission. To separate these results from laboratory measurements an apostrophy is added to the symbols, e.g. R' for the apparent sound reduction index. Otherwise the process is the same.

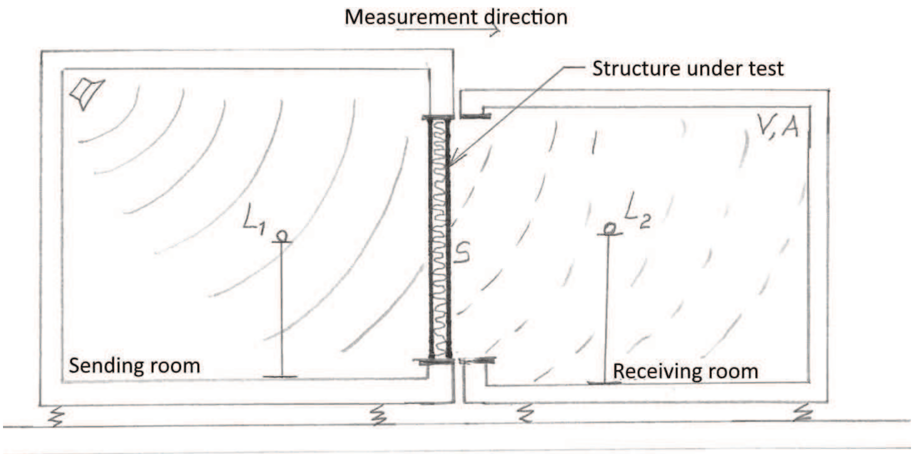


Figure 18 – Measurement setup for the sound reduction index measured in a laboratory. Adapted from [13].

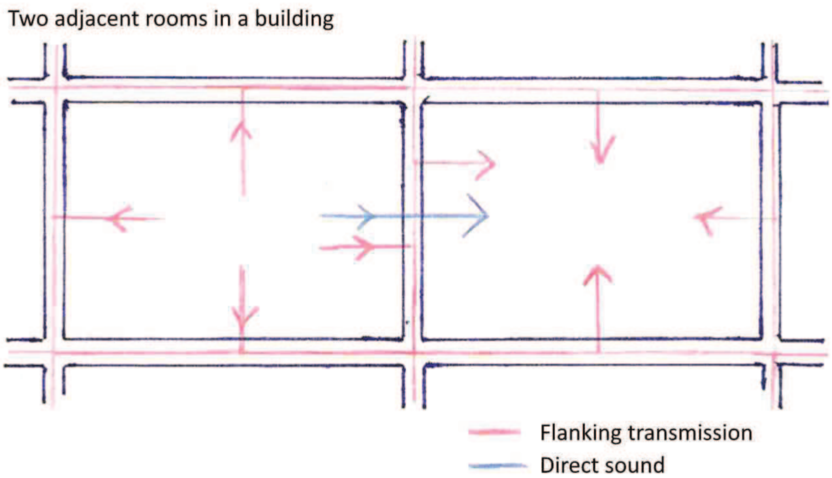


Figure 19 – Flanking transmission paths between two rooms in a building. Adapted from [15].

The sound reduction index can be defined using the incident sound power W_1 on the structure in the sending room and the power received W_2:

$$R = 10log(\frac{W_1}{W_2}). \tag{14}$$

The incident sound power can be written as a function of sound pressure p on the surface area S of the structure:

$$W_1 = \frac{p_1^2}{4\rho c}S, \tag{15}$$

where the constants ρ and c are air density and the speed of sound in air, respectively.

The power received is defined indirectly from the SPL in the receiving room. When the sound source is on and the two rooms have reached an equilibrium, the power absorbed by the absorption area A_2 in the receiving room has to equal W_2:

$$W_2 = \frac{p_2^2}{4\rho c}A_2. \tag{16}$$

The absorption area is defined from the reverberation time of the receiving room, as explained in Sec. 2.3.2.

Eventually, the sound reduction index can be calculated using only the SPLs measured in the two rooms and the areas S and A_2:

$$R = L_{\mathrm{p},1} - L_{\mathrm{p},2} + 10log(\frac{S}{A_2}), \tag{17}$$

where $L_{\mathrm{p},1}$ and $L_{\mathrm{p},2}$ are now the SPLs in the sending and the receiving room, respectively.

As pointed out earlier, the transmission coefficient, and thus the sound reduction index, can be highly frequency dependent. In consequence, the R (or R') values are calculated for several octave or 1/3-octave bands. From these values, it can be seen how well the structure insulates sound at different frequencies, but it is not practical to have a big set of numbers.

Weighted sound reduction index R_{w} (or R'_{w}) is a single number quantity that combines the knowledge from the individual sound reduction indices in one value to describe the structure. This weighted index is evaluated by comparing the R/R'-frequency curve with a reference curve for a set of frequencies in octave or 1/3-octave bands. This curve is defined in the standard ISO 717-1:2013 [28] and it is shown in Fig. 20 in red.

In the figure an example curve of apparent sound reduction indices is plotted in blue. The reference curve is placed above or below the measured curve and moved along the y-axis until the sum of unfavourable differences between the reference and R/R' values is as large as possible but less than a set limit. This limit is 32.0 dB if 1/3-octave bands and 10.0 dB if octave bands are used. A difference is unfavourable if the measured reduction index is less than the reference value.

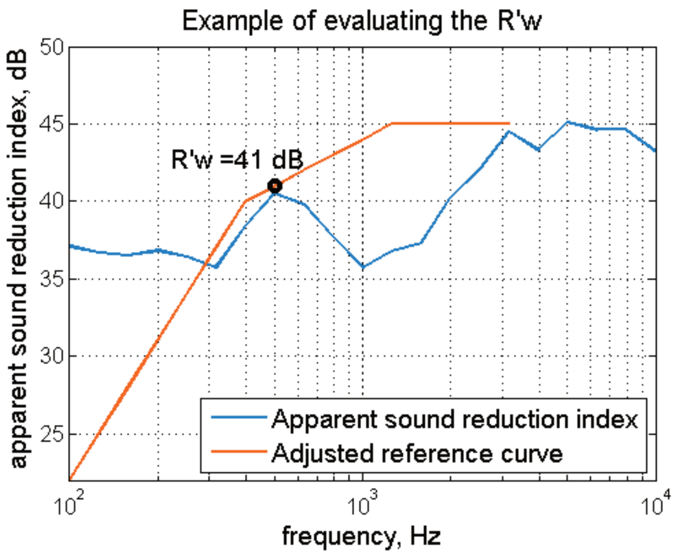


Figure 20 – Reference curve for evaluating R_w or R'_w from the measured sound reduction index curve.

The reference curve has been designed so that the single number value can be read from the point at 500 Hz. In the example in Fig. 20 the R'_w is 41 dB and marked with a black circle. This value indicates that normal conversation can be heard through the structure but the words are unintelligible. Other examples of how sounds in the sending room are experienced in the receiving room are listed in Table 4 below.

Table 4 – Weighted apparent sound reduction index R'_w and its effect on hearing speech from the other room. The receiving room has an A-weighted background noise level of 35 dB. In a normal apartment the background noise level is smaller and the descriptions in the table should be moved 2-3 rows higher. Adapted from [13].

R'_w, [dB]	Experience of speech sounds in neighbouring room
> 60	loud yelling can be heard, words unintelligible
> 55	loud speech cannot be heard
> 50	loud speech can be heard, words unintelligible
> 45	normal level speech cannot be heard
> 40	normal level speech can be heard, words unintelligible
> 35	normal level speech can be heard, words intelligible but concentration still possible
> 30	structure does not prevent from hearing sounds from the other room

In the case of doing field measurements, the values for sound insulation are usually smaller than in the laboratory measurements. The difference depends on the said flanking transmission paths and the sealing of the structures. The amount of flanking transmission is defined by e.g. the joints of different building elements, and the implementation of lowered ceilings or ventilation ducts. [13]

Airborne sound is not the only possible way to get sound transmitted from one room to another. All kinds of direct impacts on the room boundaries can cause sound to the adjacent rooms or rooms that are otherwise connected to the structure. This kind of impact sound insulation of floors is measured and quantified with methods described in [13] and [15] in Finnish, and in the standards ISO 140-7:1998 [29] and ISO 717-2:2013 [30] in English. Impact sound measurements were not done in this thesis.

In the next section the acoustic quantities presented above are observed in the library context. Especially the guideline values and requirements are shown.

2.4 Requirements for acoustics in libraries

The requirements for the acoustics in a library come from at least three sources: needs and wishes from customers, needs and wishes from the library staff, and regulations and recommendations from laws and guidelines. The first two are more qualitative and related to soundscape, which is then affected by acoustics. The third one includes values for e.g. noise levels and sound insulation. All of these are briefly presented below, the focus being the project for which this thesis is done.

The customers' point of view combines the need for certain types of spaces and the sounds in them. The wishes in [1] have been collected in Helsinki, Finland, where both quiet places for reading or relaxing, and places for meeting other people were hoped for. The silence and calmness were even more emphasised since they are not always found in the current city environment. However, the libraries should still be alive and organise events. In addition, different types of working spaces were mentioned, and especially different levels of background noise in them. That topic was already discussed in Sec. 2.2.2.

Even though customers are often the ones that have the power to give feedback on the sonic environment, the staff members cannot be forgotten. Library is their workplace and a functioning acoustics is thus important for them. The staff needs to be able and willing to work in the customer areas without getting tired or frustrated.

In [1], people from libraries in five Finnish cities told their opinions on their own sonic environment. The common ideal seemed to be a library with areas of different soundscapes, including silent rooms and more relaxed spaces. In general, the sounds of people are accepted instead of demanding complete silence. However, most of the respondents were not happy with the current acoustics in their libraries, with common problems being too much reverberation, restless soundscape and sounds getting carried too far, especially from children and youth's sections.

The third point of view is the regulations and guidelines. For libraries the regulations in Finland are related to work safety and do not take a stand on creating a pleasant acoustics in the space. Some types of spaces are too complicated and varying to be given strict limits, which is also the case with libraries. [13, 31]

Despite missing clear regulations there are guidelines in the Finnish Association of Civil Engineers manual RIL 243-2 [31] that give some reference values. It includes sound insulation, background noise level and reverberation time for spaces typical in libraries. The standards and guidelines Building Bulletin 93 (BB93) from the UK [32] and NS 8175 from Norway [33] can be used as comparison. The values given in these documents are listed in Table 5. Corresponding documents from other countries were not available.

Table 5 – Reference values for different acoustic measures in libraries, taken from RIL 243-2 (Finland) [31], BB93 (UK) [32] and NS 8175 (Norway) [33]. In RIL 243-2 the reverberation time depends on the height of the room, in BB93 it is the maximum mid-frequency value, and in NS 8175 it is the maximum reverberation in a room of the height h.

	RIL 243-2	**BB93**	**NS 8175**
Sound insulation R'_w, [dB]	44 (wall) 30 (door)	40-45	-
Reverberation time T, [s]	0.6-1.5 (main hall) 0.6-0.9 (reading room)	< 1.0 (new) < 1.2 (refurbished)	(0.13-0.27)$\times h$
Background noise level, A-weight, [dB]	38-43	40 (new) 45 (refurbished)	23-38
Mean absorption coefficient α	-	-	0.15-0.30

From the table it can be seen that the sound insulation values and reverberation times in RIL 243-2 and BB93 are similar to each other. The maximum reverberation time suggested by the Norwegian standard varies a lot more in different spaces giving example value ranges of 0.46-0.94 s and 0.78-1.62 s for room heights 3.5 m and 6.0 m respectively. The extremes are the maximum values for the most and the least strictly designed spaces, respectively. In Norway the background noise level requirement is significantly lower than in the other two.

In addition to numerical values RIL 243-2 also gives instructions on good acoustics and ways to achieve it. The main halls and reading rooms are designed following the guidelines for open-plan offices in RIL 243-3 [10], since the objectives are very similar: speech should not be intelligible between sections, or even inside one, and reverberation time should be short. The most essential considerations in library context are presented below. Special spaces such as auditoria, office rooms and cafés can be designed using RIL guidelines for those spaces, but they were not focused on in this study.

In open-plan offices, like in libraries, the sound source is most often one speaker or a group of speakers. Speech contains messages that can be understood even if one is not a part of the conversation, which can make it a distraction. It can take up to 15-20 min to get used to continuous speech and to be able to shut it out from one's mind [34, 35]. A single speaker is the most distracting while a group of more than 8 people forms a buzz of conversation easier to get used to.

Good open-plan office acoustics is built from three components: as much absorption as possible, tall screens and pleasant background noise spectrum at a high enough level. Together these result in an environment where speech is not distracting [10, 36], i.e. the STI is significantly below 0.60 as discussed at the end of Sec. 2.3.3. RIL 243-3 gives reference values for reverberation time, background noise level and sound insulation to help design this kind of sonic environment.

The reverberation time recommended for the offices varies between 0.35 and 0.60 s depending on the room height. This can require a big amount of absorption materials. When it comes to the background noise, the A-weighted level from heating, ventilation and air conditioning (HVAC) equipment should be 42 dB. The general aim is to reduce the radius of distraction by decreasing the SNR and thus the audibility of unnecessary sounds. This remark would indicate that the background noise levels in NS 8175 are too low for libraries. Instead of using HVAC equipment for masking speech sounds, a special sound masking system with a loudspeaker network in the ceiling can be used to produce an optimum masking sound at 40-45 dB.

As an end result for the requirements above, the radius of distraction r_{D} in the office is small and the rate of spatial decay of SPL per distance doubling DL_2 is large. The situation is presented in Fig. 21. In addition to the acoustics in the open-plan office area itself, the sound insulation to separate rooms has to be on a certain level. The structures between the open-plan office area and a room should result in a R'_{w} of 44 dB, unless the room uses sound reproduction in which case the value is 52 dB.

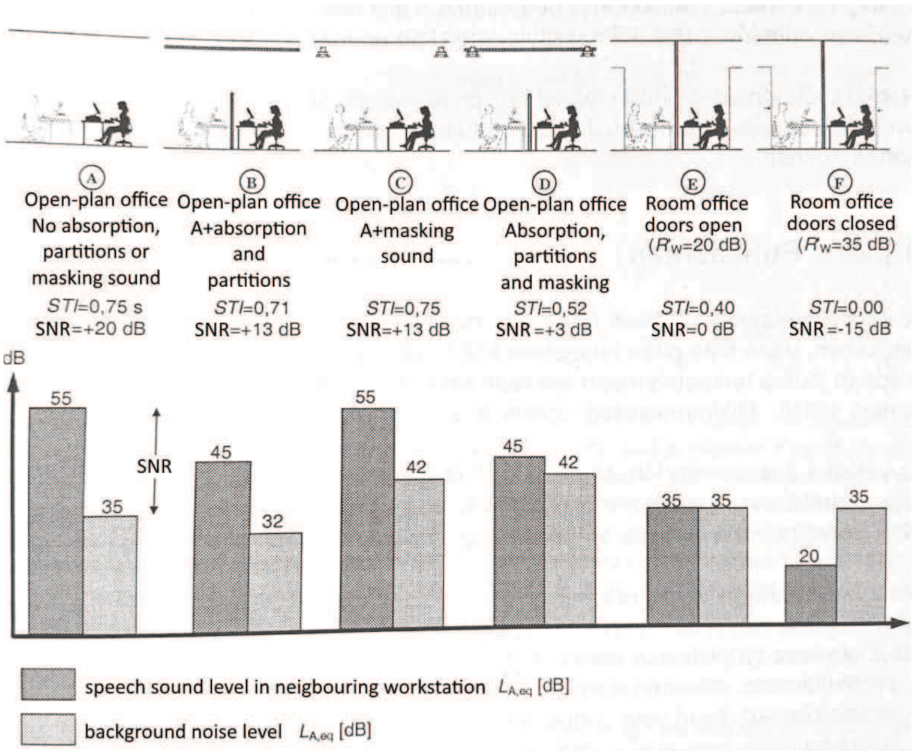


Figure 21 – Comparing an open-plan office with a room office in different acoustic conditions. The need for all three components absorption, screens and masking sound can be clearly seen. Adapted from [10].

In libraries, the instructions for open-plan offices have to be adapted. In reading rooms it is important that everyone can easily concentrate, which can be achieved with a big amount of absorption material and high enough level of background noise. The workstations are not always separated by screens like in open-plan offices, but people are also quieter and do not speak with each other.

At the same time, the main hall is a more open space where people can talk. The requirement for the reverberation is not as strict as with open-plan offices but absorption material is still needed on most of the free room boundaries. Mats or carpets help with reducing both the reverberation and footstep noises, and shelves act as screens. If the library has several floors, special care has to be taken to prevent the sound from carrying from one floor to another. [31]

In a typical library there is also an info desk. Above the desk there should be a reflector to help the staff member and the customer hear each other. Absorption material should be placed on the walls to avoid the conversation to be heard elsewhere.

As a conclusion, there is not much instruction material for designing library acoustics. Most of the information above is only from guidelines that are not necessarily taken into the design process. Already the three documents used here had quite big variations between their reference values, which might be an indication of missing research in the field. Acoustics has also only recently become an explicit concern in library design, opposing the previous view of sound being only noise from the outside [5].

The customers and librarians both hope for a generally calm sonic environment with zones of varying noise level [1]. This could probably be achieved following the instructions presented above and placing the zones cleverly with respect to each other. One problem is that the library staff is often relatively unfamiliar with controlling and designing the sonic environment, thus not knowing what to do [1].

In the following chapters the measurements on the acoustics of the five libraries participating in the project are presented. The theories above are then used for analysing the results and for giving suggestions about improvements.

3 Measurement methods and practicalities

This chapter presents the measurement methods used and shows how they were applied in each of the libraries. Related standards were taken as the basis for choosing the measurement equipment and executing the measurements themselves. Deviations from the standards are mentioned. The methods for the result analysis are presented in the following chapter.

3.1 General information about measurements

The acoustic problems found in the participant libraries, mentioned in Sec. 2.2.2, can be summarised as follows: sounds spreading too easily from children's and youth's sections to other parts of the library, too reverberant spaces and poor sound insulation. The acoustic measures chosen for evaluating these problems are spreading attenuation (including DL_2), background noise level, speech transmission index with radius of distraction, reverberation time, and weighted apparent sound reduction index R'_{w}.

Spreading sound in libraries can be observed in a similar way to open-plan offices. This means measuring spreading attenuation, background noise level and the STI, including determining the r_{D}. These three were chosen in order to investigate the effect of both speech and other sounds on people in other library sections. As mentioned in Sec. 2.3.3 and Sec. 2.4, speech can be very distracting as background noise, and the STI is a relatively good measure in evaluating its intelligibility. Monitoring background noise in turn allows determining the needed SNRs, and comparing the levels in libraries to the recommended background noise level.

Reverberation time is rather simple and quick to measure, and it is commonly used to describe how reverberant a space is. It is also needed in computing the STI. The spaces in a library can vary significantly along with the reverberation time in them, but the measure is still a useful one even if one common set of values could not be determined. In case of clearly varying reverberation times, zones of different reverberation can be separated. Thus it is also possible to concentrate on the really problematic areas.

Sound insulation is quantified by calculating the R'_{w} used both in standards and guidelines. It is the quantity that is announced for structures that should insulate sound, and it is used for confirming that the structures in a building follow the sound insulation regulations [13].

The choice of this set of measures is also justified by the fact that there are standards for measuring the quantities needed. They are briefly presented after the measurement equipment.

3.1.1 Measurement equipment

The measurements are mainly executed so that the processing can be done afterwards. This means using a loudspeaker as the sound source and a microphone as the receiver. An external sound card is connected to the recording computer to ensure good sound quality and to avoid possible processing done by the internal one. A hand-held recorder and a sound level meter are also used. The devices are shown in Fig. 22.

(a) (b)

(c) (d)

(e)

Figure 22 – The measurement equipment: a) loudspeaker, b) microphone, c) external soundcard, d) hand-held recorder and e) sound level meter.

The loudspeaker is a Genelec 1029A. It is a studio monitor which is mainly meant for that purpose resulting in a frequency dependent directivity, far from omnidirectional (Fig. 23). On one hand, in many of the standards presented below omnidirectionality is required but evidently not achieved with this loudspeaker. Thus, the room excitation depends on where the source is facing, and that can affect the results. On the other hand, the directivity resembles a human speaker (Fig. 14), which is the main sound source in the libraries. This loudspeaker is sufficient for this study but it still should not be used as a replacement for human head in more precise measurements [37].

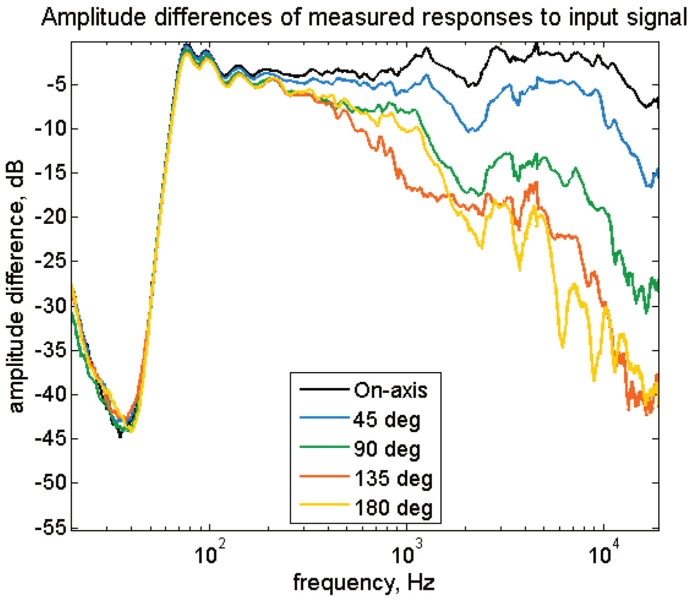


Figure 23 – Angular frequency response of the Genelec 1029A loudspeaker. This characterisation was done in an anechoic chamber.

The measurement microphone is a Behringer ECM8000 omnidirectional condenser microphone. Its frequency response is flat across the audible range, apart from < 5 dB ripple at frequencies 4-10 kHz.

Both the loudspeaker and the microphone are connected to an external USB sound card Focusrite Scarlett 2i4. The loudspeaker uses a 6.3 mm audio jack on the card, converted to XLR at the loudspeaker's end. The microphone is connected using a normal XLR microphone cable, and it gets the phantom voltage directly from the connection. Since the card is mainly aimed for musicians, it is simple to use. For instance, it has an easy way to check possible clipping in the recording channel by indicating the received level with a coloured light around the gain knob.

The microphone cannot be used in the sound insulation measurements since it has to be connected to the computer with a microphone cable. To avoid crushing the cable under doors, a hand-held SPL meter connected to a recorder is employed. This way the quality of the microphone of the SPL meter is combined with the possibility of post-processing.

SINUS Tango sound level meter is a Class 1 (IEC 61627) hand-held device. Its measurement range for an A-weighted equivalent level L_{Aeq} is 30-140 dB, which is sufficient for the measurements in this thesis. It is also equipped with a 3.5 mm audio jack for recording the signal received by the microphone. In addition to the main function in the sound insulation measurements the meter is also used for setting the sound source level and for occasionally taking notes of SPLs during the spreading attenuation measurements.

The audio jack of the sound level meter is utilised with Zoom Handy Recorder H4n. This recorder allows using external microphones for capturing the sound and then saves it as a .wav file. The sampling frequency can be adjusted, here it is 44.1 kHz. Later on, sound samples for the subjective library comparison are recorded with the recorder alone.

The measurement signal for measuring all but the sound insulation is a combination signal. It includes all the signals needed for acquiring spreading attenuation, impulse response, background noise level and STI. The sampling frequency is chosen to be 48 kHz, and the whole signal takes approximately 41 seconds. The signal consists of silence, a sine sweep and pink noise, as shown in Fig. 24. The levels for the sweep and the noise sequences were tuned so that sufficient SPLs are achieved with the noise without the sweep getting distorted in the loudspeaker.

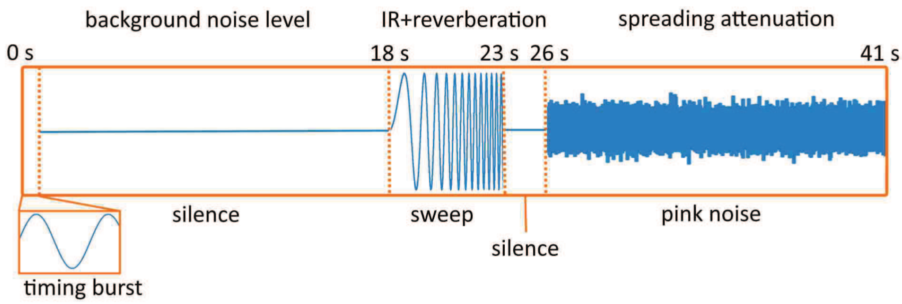


Figure 24 – Schematic of the measurement signal used for measuring spreading attenuation, background noise level and impulse response. Above the signal the role of each part is indicated. Below, the type of the signal is written. The timing burst is used for aligning all the measured signals to have their start at approx. the same index in the analysis.

In case of measuring only the reverberation, the sine sweep is used solely. When it comes to measuring sound insulation, it does not require special signals. A long sequence of pink noise is used for measuring the SPLs in both spaces, and a shorter one for determining the reverberation time.

The software used for the measurements is Audacity. It is a free open-source program that can be used for recording and editing multi-track sounds. It is simple to use and the recording parameters can be set. In this thesis, Audacity both plays and records the measurement signals simultaneously.

3.1.2 Standards

Standard ISO 14257:2001 [38] describes measuring sound distribution in workrooms, and it was referred to when measuring spreading attenuation in the libraries. However, the measurement environment in the standard vastly differs from the conditions in the libraries and many of the instructions must be adapted.

In the libraries the spreading attenuation is measured across the space as a network, not on one path only. The microphone and loudspeaker are put at a height of 1.55 m, as suggested by the standard, but there are going to be several obstacles between them and closer to them than instructed. Seven octave bands, 125-8000 Hz, are used for the analysis, which is more than required by ISO 14257. The SPL level from the speaker is set so that the measured SPL is at least 10 dB higher than the background level, if by any means possible. Libraries can be big and in some remote measurement positions it is possible that this level difference is not fulfilled.

The standard ISO 3382-2:2008 [39] is followed for the room's impulse response (IR) measurements, which allow determining the reverberation times. More specifically, the integrated impulse response method using sine sweep is chosen to achieve better SNR. The engineering method with six measurement positions should give accurate enough results for the purpose of this thesis.

The measurement and the computation of the STI are demonstrated in the standard IEC 60268-16:2011 [20] from which the indirect measurement method is followed. In the indirect method, the IR is measured at each point of interest. The SNR needed for the computation can be determined using the results from the spreading attenuation measurement. The standard used for acquiring the IR is ISO 3382-2 above, opposing the newer standard suggested in IEC 60268-16.

For measuring the airborne sound insulation the standard ISO 140-4:1998 [27] is used. It has been replaced by a newer standard in 2016 but this one was available at the time of this thesis. The process demonstrated for a moving microphone is followed, with two limitations. Firstly, a good steady sound in the source room is hard to achieve. The source room is often the main area of the library, which is enormous compared to the loudspeaker. This is solved by placing the loudspeaker sufficiently close to the structure measured, but still far enough to avoid it directly affecting it. A similar arrangement was used in all the libraries for consistency.

Secondly, at higher frequencies the required level difference between the received sound and the background noise level might not always be obtained. This is due to the limitations of the loudspeaker. The reverberation time of the receiving room is estimated as described in ISO 3382-2 for interrupted noise method.

In the following section the libraries and the practical arrangements in them are explained.

3.2 Library-specific procedures

Each one of the five libraries has very different facilities. Some have several floors, others only one. For the means of comparison, the spreading attenuation and the STI for children's and youth's sections and the reverberation time are measured in every library. Sound insulation is measured if needed. The characteristics and problems in the libraries vary, which is why the measurement procedures are presented below, library by library.

3.2.1 Entresse Library, Espoo

Entresse Library is located in the top floor of a shopping centre called Entresse, opened in 2009. The library has all its functions in one level and most of them are in the same open space. Some services, such as silent reading, auditorium, story room and workshop, are separate glass walled cubes acting as some kind of screens between different areas. The surface area is 2700 m^2 and the total volume approx. 8300 m^3. The general look of the library and the materials used there can be seen in Fig. 25.

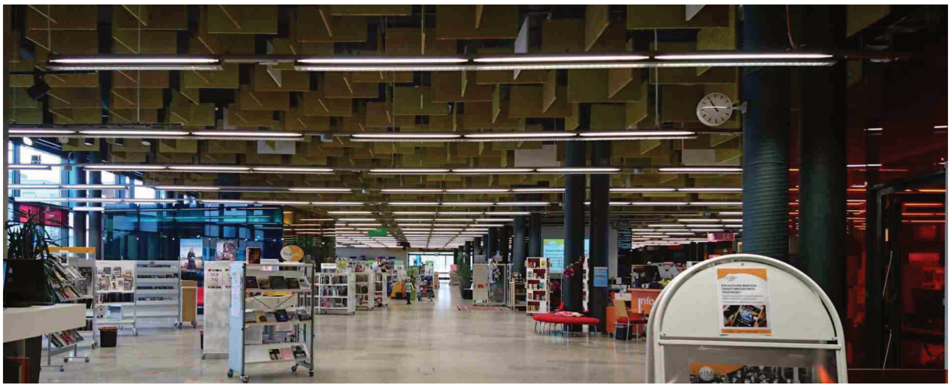


Figure 25 – General look of Entresse Library. The picture is taken from the entrance. The floor is made of stone and the ceiling is covered with acoustic tiles. Most of the wall surfaces are made of glass.

The problems encountered by the staff and the customers can be summarised to the disturbance caused by children and the youth. Children's section is in the open area and all kinds of sounds from there can be heard quite clearly in the neighbouring sections. Youth's section in turn is in a separate wing but it is still connected to the main space. People working and studying outside the silent reading room have been experiencing distraction because of the sounds, and they are offered ear plugs.

To measure the spreading of the sound from the children's and the youth's sections, the combination measurement of spreading attenuation and STI is conducted. The idea is to place the loudspeaker in the middle of each section, to point it towards the other areas of the library, and to measure in a range of points forming a grid across the space. This way the development of the measures in the space can be mapped. In this library, the grid density is approximately 8 m. The arrangement is demonstrated in Fig. 26.

Both the loudspeaker and the microphone are set on a stand, at a height of 1.55 m. The microphone is pointing upwards, and the stand is kept as compact as possible to avoid getting reflections from it. The directivity of the loudspeaker can become effective, and the direction is thus written down.

Before measuring throughout the grid, the SPL emitted by the loudspeaker with pink noise is tuned to a desired level of 85-90 dB at 1 m in front of the speaker. The SPL in the furthest and most silent place is also checked for having a big enough margin to the background noise level. The sound level meter is used for doing this. When the tuning is done and the recording channels are checked for clipping, a reference measurement is recorded at that 1 m spot.

Figure 26 – Measurement grid as blue dots for spreading attenuation and STI in Entresse Library. The sources for the two sections are marked as orange dots named S_1 (children) and S_2 (youth), and they act as a measurement position for the other source's measurement round. The arrows show where the loudspeaker face is pointing.

3.2.2 Lappeenranta City Library, Lappeenranta

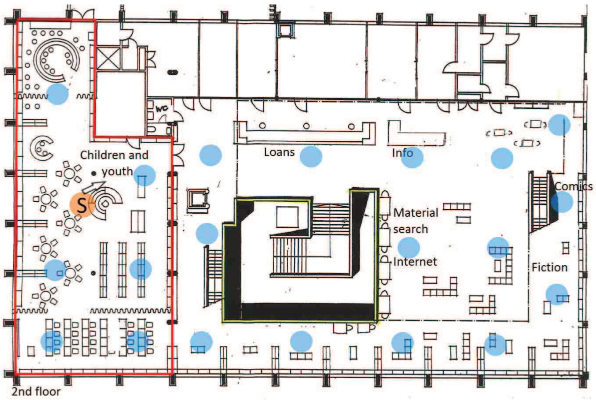
Lappeenranta City Library is located in the oldest facilities out of these five participants: the building was opened in 1974. The services of the library are divided into three floors. The floors are connected through a staircase in the middle of the building, with each floor having less surface area than the previous one. Fig. 27 illustrates the situation and shows the surface materials.

Figure 27 – View from the balcony of the 3rd floor in Lappeenranta City Library. Parts of all the three floors can be seen. The ceiling is painted concrete with windows in each recess. The floors are clinker tiles and linoleum.

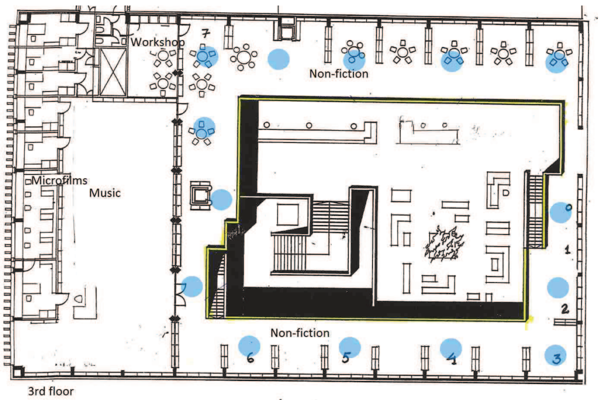
A reading room, magazines and an auditorium are situated in the bottom floor; the actual library then takes up the other two floors. The youth's and the music sections are both separate rooms that can be closed with doors, while the other sections are parts of the open space. The total surface area and volume are approx. $2700\ \mathrm{m}^2$ and $8900\ \mathrm{m}^3$. Not all of these facilities are included in the measurements.

The problems highlighted by the staff are too much reverberation in the main hall, sounds spreading easily from one floor to another and insufficient sound insulation in the reading room. The reading room is affected by two adjacent spaces: the entrance hall and the auditorium that is often used for music events. A glass door to the hall and a thick auditorium wall separates the rooms from each other. The auditorium is also located behind the reading room so that it is accessed by walking through the space.

The spreading attenuation and STI measurements are conducted in the same way as explained above. The loudspeaker is placed inside the children's section and the main emission is aimed out from the doors separating the section from the main hall. The measurement grid expands over the 2nd floor and the 3rd floor balcony that is connected to the main area (Fig. 28). The grid density is approx. 8 m.



(a)



(b)

Figure 28 – Measurement grid as blue dots for the STI in Lappeenranta City Library, a) 2nd floor and b) 3rd floor (balcony). The source is marked as an orange dot named S, and the arrow shows where the loudspeaker face is pointing.

Because the children's and the youth's sections are combined, only one set of recordings is obtained. Thus, another source location and three measurement positions are required for the reverberation time measurement. This arrangement is shown in Fig. 29.

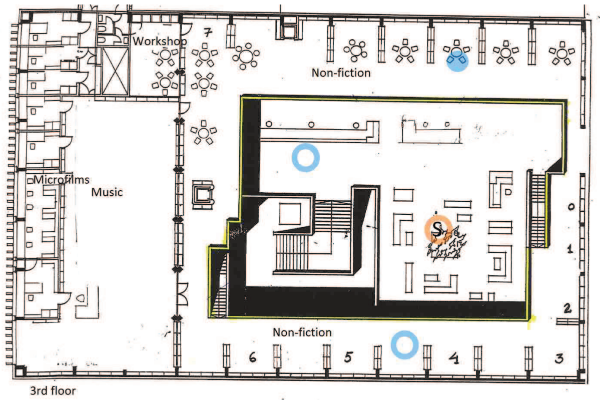


Figure 29 – Measurement arrangement for reverberation of the main hall in Lappeenranta City Library. The source S (orange ring) is placed on the 2nd floor with two measurement positions (blue rings) and one measurement position is on the balcony (blue dot).

To investigate the sound insulation situation with the reading room, the sound reduction is measured. Both the entrance hall and the auditorium act as source rooms while the reading room is the receiver. Two source positions are used in each source room, for which two measurements in the source room and three measurements in the reading room are saved. The arrangement is illustrated in Fig. 30.

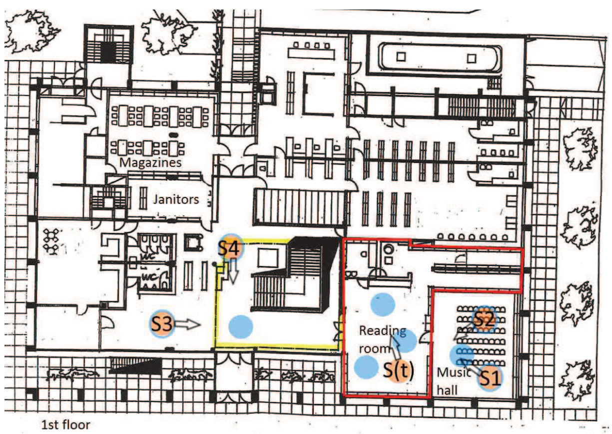


Figure 30 – Measurement arrangement for measuring the airborne sound insulation of the reading room in Lappeenranta. Auditorium and entrance hall act as sending rooms with loudspeaker positions S_{1-2} and S_{3-4}, respectively. S(t) is used for measuring the reverberation of the receiving reading room. The measurement positions are marked as blue dots or blue circles in case it is also a source position.

The measurement process goes as follows. The loudspeaker is placed in a source position, and the volume level is set high enough to result in a SPL of at least 15 dB above the background level in the receiving room. The background level is also saved. After setting up a 15 s recording is saved at each measurement position. In different source positions, the loudspeaker is put to heights 1.2 m and 1.55 m to excite different horizontal planes. At the end the loudspeaker is placed in the reading room, and the interrupted noise is measured twice in each measurement position, six times altogether.

The sound level meter acts as a microphone that is moved during the SPL measurement. It is held at the end of a straight arm of the measurer, and moved around the measurement position. The clothes of the measurer are chosen to avoid extra sound. For the reverberation time, the sound level meter is again held likewise but now still.

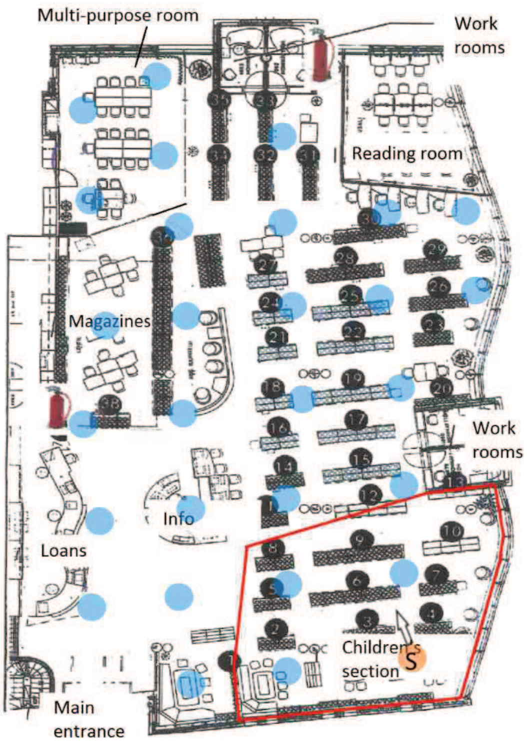
3.2.3 Malmi Library, Helsinki

Malmi Library is part of the culture centre Malmitalo, opened in 1994. It is a small library that still includes a reading room, individual workrooms and a multi-purpose event space with a movable glass wall. The general look from the entrance and the materials can be seen in Fig. 31. The surface area and volume are 630 m^2 and 3500 m^3.

Figure 31 – Malmi Library seen from the entrance. There are areas with higher and lower ceilings with perforated tiles and painted concrete surfaces, respectively. One wall is made of bricks, but some have acoustic tiles. The floor is clinker tile and linoleum.

In this library, the compactness of the space lets sounds from all parts of the library travel almost everywhere. Due to this and the occasional high noise level of children, their section is regarded as a problem. The high ceiling and general reverberation combined to it were also mentioned as an issue. When it comes to the multi-purpose room, it is used for e.g. author visits and children's story sessions. The glass wall is then closed but the sound insulation is found to be insufficient. Occasionally, the people in the reading room are disturbed by noises from the main area.

All quantities are measured in Malmi Library in the same way as in Lappeenranta. First, the spreading attenuation and STI set is conducted, after which the additional source and measurement positions are measured for the reverberation. Fig. 32 shows the arrangements. The grid density this time is approx. 4.5 m.



(a) (b)

Figure 32 – a) Measurement grid as blue dots for the STI in Malmi Library. The source S is marked as an orange dot and it is facing along the arrow. b) Second source position and measurement positions for reverberation.

The sound insulation is measured for two rooms: the reading room and the multi-purpose room. The rooms are so close to each other that three source positions in the sending room suffice. Otherwise the procedure is as described above for Lappeenranta City Library, and graphically demonstrated in Fig. 33. The glass walls in the multi-purpose room are completely closed during the measurement

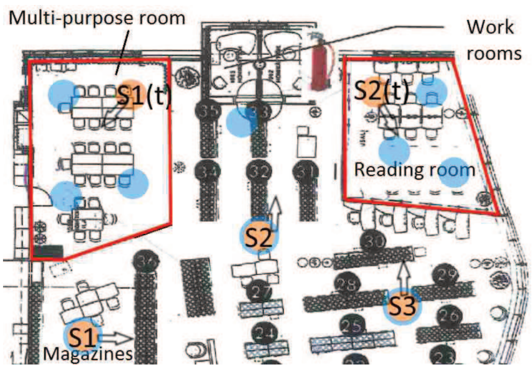


Figure 33 – Measurement arrangement for sound insulation in multi-purpose and reading rooms. For each source the other points in the sending room are measured for the SPL.

3.2.4 Vihti Communal Library, Vihti

Vihti Communal Library was designed already in 1989 but eventually built later, modified, and opened in 1998. The style is simple and industrial, and the majority of areas meant for the public is in one common space (Fig. 34). The surface area and volume are approx. $1350\ \mathrm{m}^2$ and $6800\ \mathrm{m}^3$. The main area takes up the height of two floors and the biggest wall is a large window. The second and third floors are balcony-like structures. In the first floor there are also reading rooms and an event space that used to be a café.

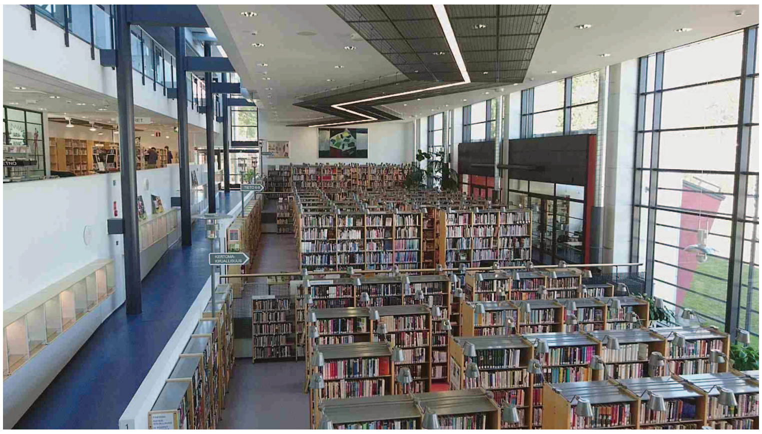


Figure 34 – Overall look of Vihti Communal Library. The space is very open and most of the materials are hard: painted concrete, linoleum, plastic mats, plaster board and glass.

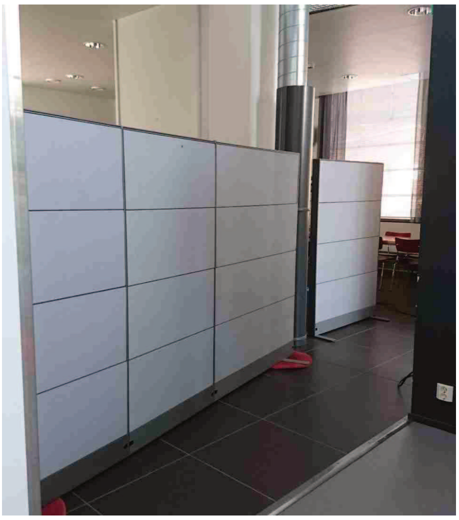
All of the acoustic properties measured in this thesis are seen as big problems in this library. The main area is highly reverberant and open, and sounds are both loud and easily heard across the library. Again, the sounds from children and the youth are experienced as the most disturbing, and the problem arises even if there are only a couple of children speaking. In addition, the event room is difficult to use, since it does not have proper walls but uses screens that do not fill the full height of the room.

In this library, the children's and the youth's sections are separate. This means that all the three quantities spreading attenuation, STI and reverberation time can be measured at the same time. The measurement grid extends through all of the large common area (Fig. 35) with the density being approx. 8 m in the first floor and 6.5 m upstairs.

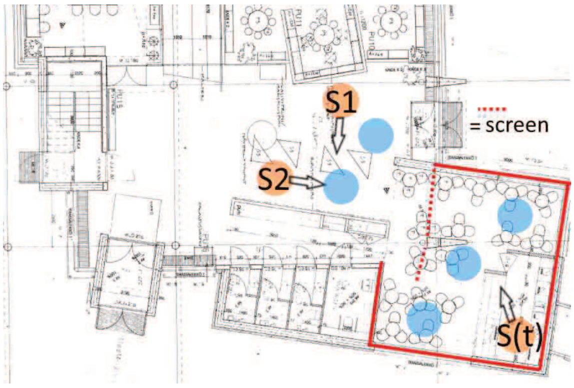
The sound insulation in the event room is completely measured with the screens in normal positions, after which the effect of moving them is tested quickly with a reduced amount of recordings. The normal position and the measurement arrangement can be seen in Fig. 36. The room is also measured from both source positions with both screens closed, saving one recording. Lastly, both screens are removed and for the source position 2 all three points in the event room are recorded.

(a) (b)

Figure 35 – Measurement grid for the STI in Vihti Communal Library. a) The orange source point S_1 (youth) upstairs acts as a measurement position when the loudspeaker is placed at b) S_2 (children) downstairs. The arrows show where the loudspeaker is pointing.



(a)



(b)

Figure 36 – a) Event room in Vihti Communal Library is separated from the main hall by two office screens. The second one does not completely close the gap between the pillar and the wall. b) Measurement arrangement for measuring the airborne sound insulation. The dotted line shows the normal positions for the screens. S_1 and S_2 are the source positions in the sending room and S(t) is for measuring the reverberation of the receiving event room.

3.2.5 Seinäjoki Main Library (Apila), Seinäjoki

Seinäjoki Main Library's newer building Apila has a special status in this project as the reference library. All the other libraries are to be compared to it. It is very new, opened in 2012, and special attention has been put to shaping the sonic environment in the facilities. The space is divided into three levels, where all bigger sections are clearly separate areas. However, none of them are fully enclosed by walls. This makes the spaces be connected to each other, but at the same time they might have their own acoustic environments. Figures 37 and 38 illustrate this and the material choices. There are also a reading room and an auditorium, which are closed spaces with thick walls. The total surface area and volume are approx. 1800 m^2 and 10300 m^3.

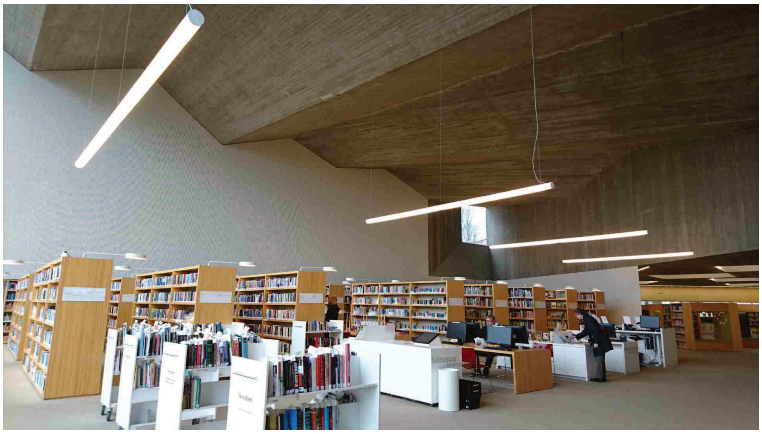


Figure 37 – View of the main hall in Apila. The entrance of the children's section is on the right. The main material of the ceiling is concrete but all possible walls are covered with absorption material, even the back walls of the bookshelves. On the floors there is durable carpet.

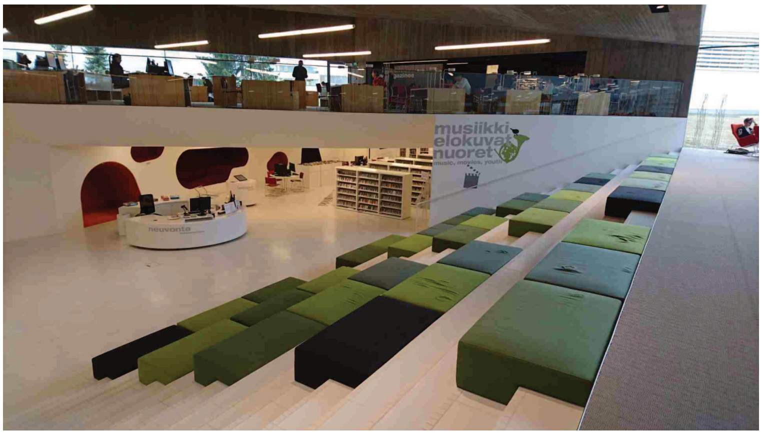
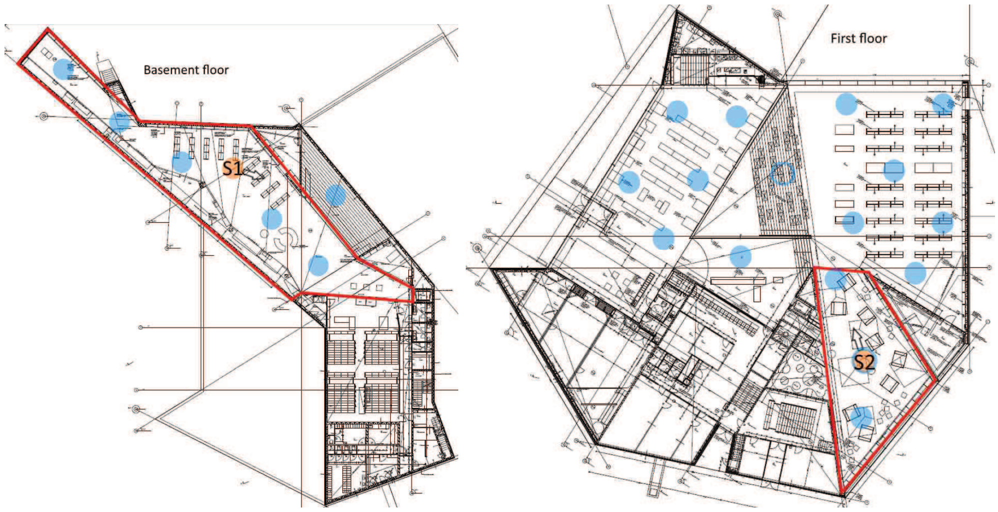


Figure 38 – The youth and music sections on the bottom level and the news area on the top one. The stairs work as seats for audience in case a performance is held in the music section. The floor on the bottom level is made of tiles. One of the walls has reading corners covered in red shag-pile fabric.

Since Apila is the reference library, all measurement types are performed. In case the children's and the youth's sections are acoustically separated enough from the main hall, the reverberation measurements are carried out separately. The measurement patterns (Fig. 39 and Fig. 40a) follow along the same lines as in the other libraries. The grid density is approx. 10 m.

The sound insulation is only measured for the reading room. The shape of the room is more complex than in the other libraries: two walls in the same space and a very sharp angle between them, as can be seen in Fig. 40b. Wherever the source is placed, some sound is transmitted through both walls. The solution is to use three source positions and measure the SPL twice close to each wall. This way the acoustic power W_1 in Eq. (14) from both walls can be estimated.



(a) (b)

Figure 39 – Measurement grid of blue dots for the STI in Apila. a) The source S_1 is placed in the youth section and b) S_2 in the children's section. S_2 acts as a measurement position when the source is placed at S_1. The arrows show where the loudspeaker face is pointing.

(a) (b)

Figure 40 – a) Measurement arrangement for measuring the reverberation time of the main hall in Apila. When source is placed at S_1, S_2 acts as a measurement position and the blue dot next to it does not. When the source is at S_2, all the blue dots act as measurement positions. In b) is the arrangement for measuring airborne sound insulation of the reading room. For each source point S_{1-3} in the sending room, measurements are taken in all blue dots. S(t) is for measuring the reverberation of the receiving reading room.

4 Results

In this chapter, the results from the measurement round are presented and analysed. Each measure is compared to the recommendations in Sec. 2.4 and to other libraries, especially Apila as it is the reference. Possible remarks on the measurement and analysis process are listed.

First, the reverberation times in different libraries and various areas in them are calculated. The second section briefly shows what kind of background noise levels the libraries had and how they compare to the ideal masking noise. In the third section the results for the spreading attenuation and the STI are analysed, after which the sound insulation results are presented.

The measurements were performed on April 8-10 and 16-17 2016. The measurement hours were either before or after the library opening hours to avoid all possible extra sounds during the recordings.

4.1 Reverberation in different spaces

The idea of using sine sweeps for measuring room IRs came from A. Farina [40]. The recorded sweep contains the impulse response needed for estimating the reverberation time, but it requires further processing. For analysing the reverberation time from the composite signal, the sine sweep first needed to be extracted, including the reverberation after it.

In Farina's method, the recorded sweep is convolved with the time-inverse of the non-reverberant input sine sweep. As a result, an IR from the loudspeaker to the measurement position was obtained, and by converting this IR into decibels a similar situation to Fig. 8 in Sec. 2.3.2 was achieved. Following the standard ISO 3382-2 this spiky curve was then smoothed using backward integration introduced by M. R. Schroeder [41]. Finally, a straight line was fit to the smoothed decay in the decibel range -5...-25 dB for T_{20}. The reverberation time could now be calculated from the slope of the line. The process is visualised in Fig. 41.

The reverberation time is frequency dependent and one number determined from the full-band decay does not tell the whole truth. This is why the analysis was done in octave bands. The full-band response was divided into seven octave bands 125-8000 Hz and the analysis process was performed to each of them separately.

The engineering method chosen from the standard required six measurements altogether. When the spreading attenuation and STI recordings were used for the IRs, suitable measurement positions had to be picked from the grid. More attention was put to the reverberation in the main halls, from where three measurements per source position were selected. Those position sets were either the same or different. The reverberation times in the six measurements were then averaged to obtain one reverberation time curve.

In addition, many of the libraries had other areas of different reverberation times. For the sake of comparison, 2-3 points from the spreading attenuation and STI measurements were used to obtain the reverberation time estimates for these spaces. This corresponds to the survey method in the standard.

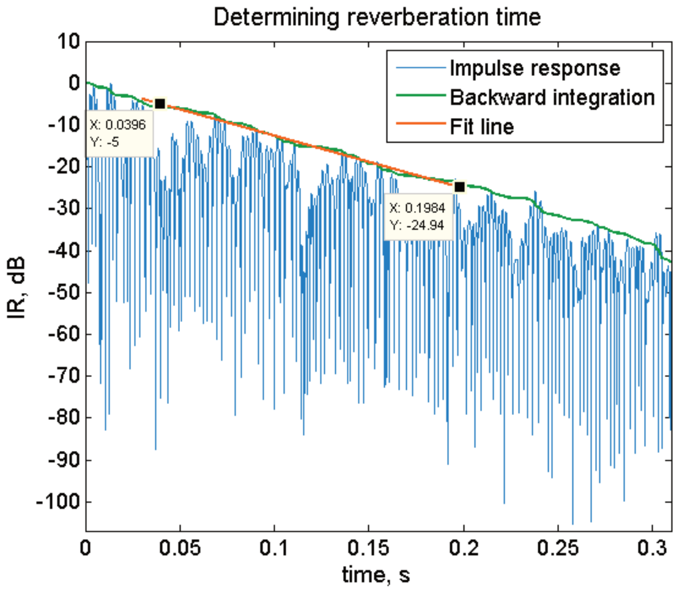


Figure 41 – Visualisation of the process for determining reverberation time. The slope of the fit line can be used for calculating the time it takes for the sound to decay 60 dB.

4.1.1 Library-specific results

Below the reverberation times for each library are presented. In the graphs, the frequency dependency is shown as a curve on which the standard deviations of the measurement results are marked as bars. The maximum reverberation times from each recommendation document are marked with a dotted line. It should be noted that the Norwegian recommendation is dependent on the room height (Sec. 2.4). The height of the main hall was used to determine this maximum value.

In Entresse the reverberation times were as shown in Fig. 42. The times are mostly at the low end of the Finnish recommendations (RIL 243-2) and fall within the ranges used in the UK (BB93) and Norway (NS 8175). Only the lowest frequencies reverberate longer. The youth's section reverberates even less than the main hall, probably because it is a smaller space and the ceiling is lower. In the main areas the ceiling is covered in acoustic tiles, as seen in Fig. 25, which reduces the vertical reflections and contributes to the short times.

The main hall in Lappeenranta City Library was clearly more reverberant than in Entresse (Fig. 43). The values just fall within the ranges in the Finnish and Norwegian guidelines but only fulfils the British ones at high frequencies. In any case, the values are at the very high end of the ranges up to 2 kHz. Possible reasons are the hard surface materials and the tall open space in the middle of the hall. The youth section is closer to the reverberation times achievable in bedrooms, being below 0.6 s at all frequencies. This is due in part to the room height 2.5 m being around the normal height in apartments, and the bookshelves aiding in dividing the space.

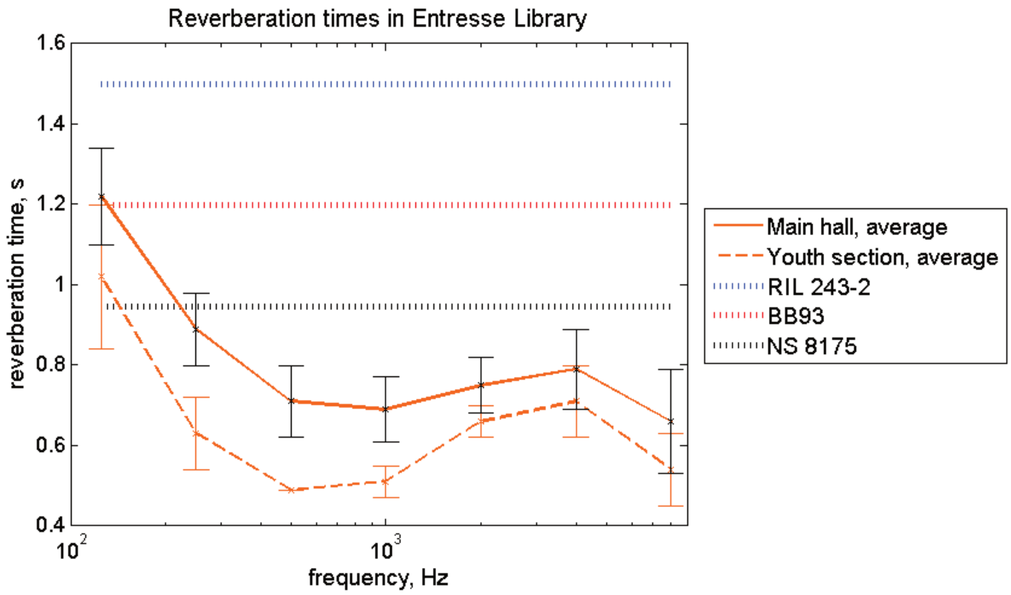


Figure 42 – Reverberation times in Entresse Library.

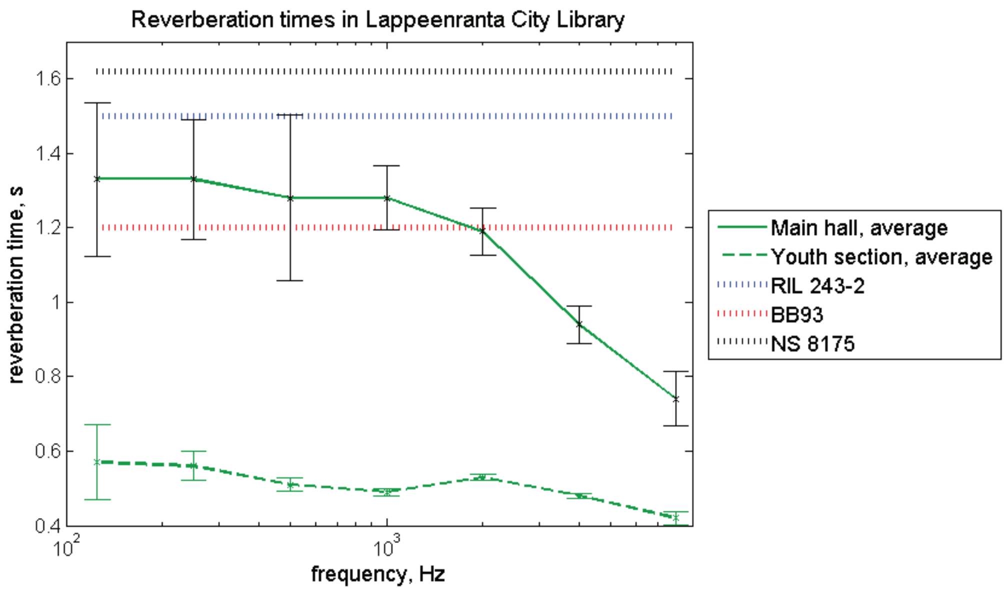


Figure 43 – Reverberation times in Lappeenranta City Library.

Malmi Library was a uniform space that did not have much variations between the reverberation times in different areas. The curve obtained for the main hall is presented in Fig. 44. The values are in the middle of the Finnish recommendations but at the higher end of the UK and Norwegian ones. Compared to the size of the library, the times are relatively long, which might be the reason why the space feels too reverberant. The materials are also mostly hard and the bookshelves do not help restrict the reflections.

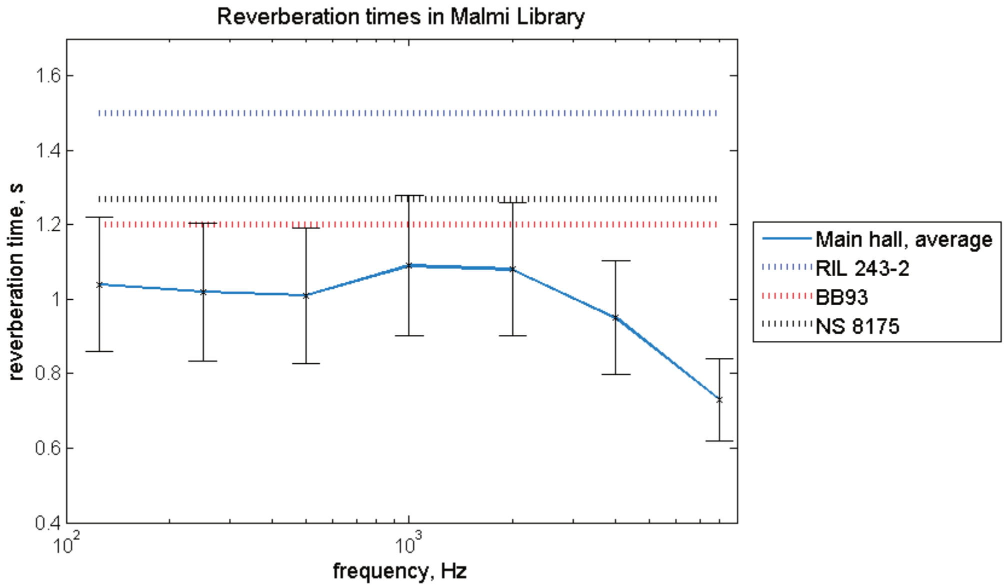


Figure 44 – Reverberation times in Malmi Library.

The reverberation times in Vihti Communal Library resembled the ones in Lappeenranta. Fig. 45 shows how the times are around 1.3 s at lower frequencies and start getting shorter only at frequencies higher than 2 kHz. The values obtained in the second floor are slightly smaller, probably due to the smaller room height. However, it is well connected to the first floor and the reduction is barely visible. The values compare to the recommendations in the same way than in Lappeenranta, meaning that they are either at the high end of the ranges, or even above. Most of the materials in the library are hard and the volume taken up by the bookshelves is proportionally small, resulting in very little absorption.

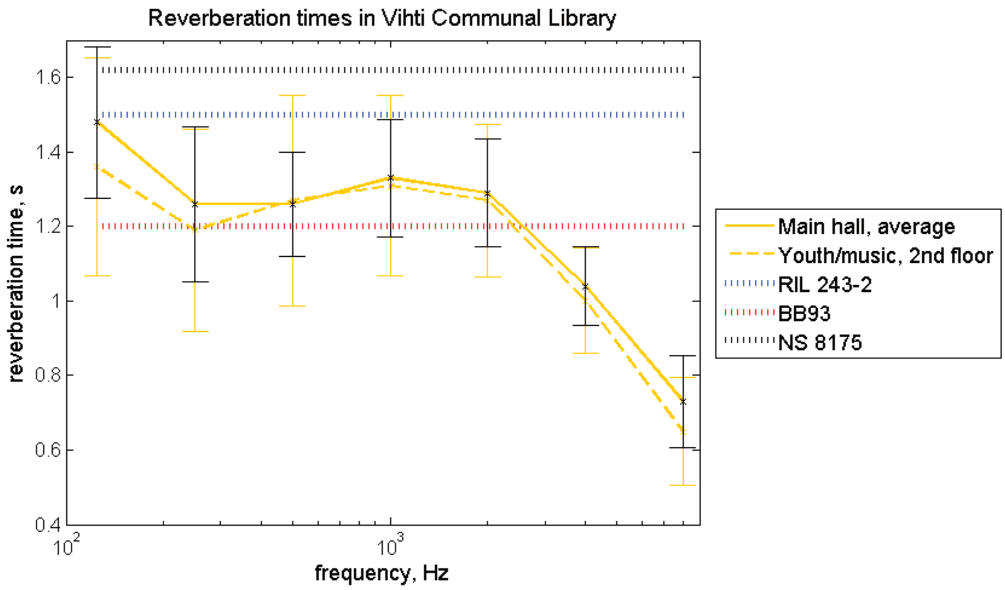


Figure 45 – Reverberation times in Vihti Communal Library.

The Apila building of Seinäjoki Main Library has most of its areas connected to each other but relatively separated, as mentioned in Sec. 3.2.5. The claim about different acoustics in those sections is supported at least by the reverberation times, as can be seen in Fig. 46. The main hall is the highest room in the library (8.9 m) and has also the longest reverberation times. The values are at the high end of the Finnish recommendations, above the ones in the UK, and at the low end of the Norwegian range. Most of the surfaces are either concrete or glass but the floor and some of the walls have absorption on them, limiting the reverberation.

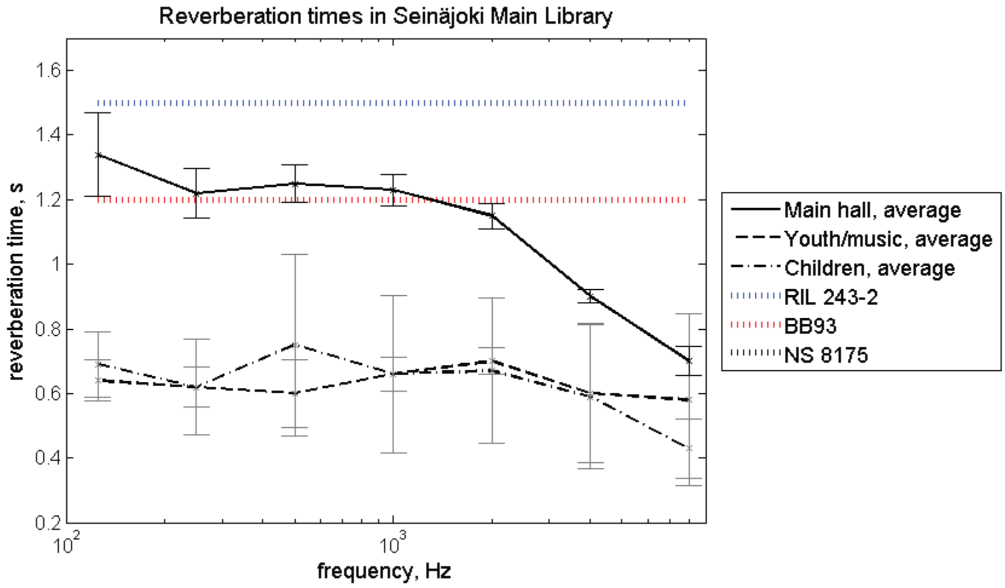


Figure 46 – Reverberation times in Seinäjoki Main Library. The maximum value based on the Norwegian standard is at 2.4 s.

The youth's and children's sections in Apila are lower, with a room height of 2.5 m. Even though the youth's section has proportionally more hard surfaces, the reverberation time is the same than in the children's section, and significantly shorter than in the main hall. The recommendations from all three documents are fulfilled.

4.1.2 Comparison of main halls

In Fig. 47 the reverberation times in the main halls of the five libraries are shown together for easier comparison. Three out of the five main halls measured were at the high end of the range in the RIL guidelines, and four out of five had a long reverberation time compared to the volume of the space. Neither the reference library had short enough reverberation. The three most reverberant ones have very similar curves and all of them had high reflective ceilings, but the shapes, volumes and the amounts of absorption material varied. The least reverberant main hall in Entresse was low and had the ceiling covered in absorption material, controlling the sound significantly more than the other main halls.

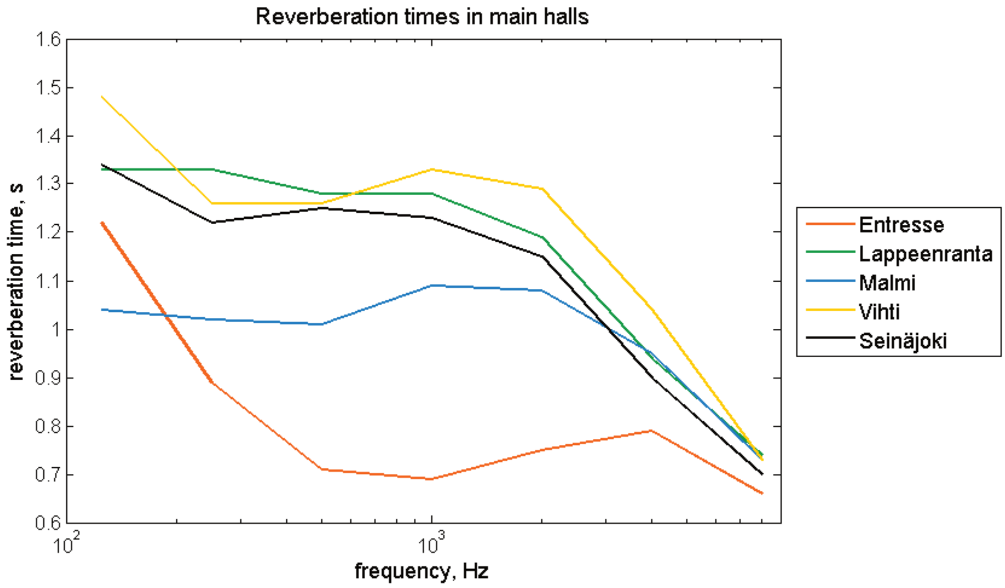


Figure 47 – Reverberation times in the main halls.

The measurement uncertainties for the reverberation times in the main halls can be estimated from the standard deviations. Since the facilities of the libraries have very complicated shapes and locally varying reverberation times, the values can vary. In these measurements the range was mainly from 0.1 to 0.2 s. In Entresse the deviations were somewhat smaller. The other reverberation times shown had values close to 0.3 s at individual frequency bands, which can be a result of using fewer measurement positions in the analysis.

4.1.3 Remarks

While analysing the reverberation times from the spreading attenuation and STI recordings, some nonidealities were noticed. For example, the level difference between the background level and the peak of the decay curve was not always large enough in all octave bands. According to the standard, the difference should be at least 35 dB when calculating T_{20}, but in some recordings it was even less than 20 dB. The loudspeaker should have been operating at a higher level, but that would have driven the speaker very close to its upper limits. This would have distorted the sound. The positions having this problem were avoided, if possible, when choosing the ones taken into account in the reverberation calculations.

Other factors affecting the measurements in a negative way include positioning the microphone close to reflective surfaces. The libraries were all in normal use and the rooms were filled with bookshelves and other equipment. The microphone was placed where possible, which in some cases meant between two shelves. Since the loudspeaker was not omnidirectional, the main direction of emission might also affect the room excitation. In addition, the loudspeaker was often not in the main hall, if the spreading attenuation and STI recordings were utilised.

Before the measurements, time was taken for photos and video documentation. During these moments, only Entresse did not feel too reverberant to the author. In Apila the situation varied significantly between being in the reverberant open space or between the shelves. The shelves seem to have been constructed so that in between them the acoustic space feels clearly smaller than what the main hall is. This was not visible in the results of individual measurements.

All in all, the results from the reverberation time measurements indicate that excessive reverberation and lacking control of it are common problems in libraries. This was true also in the reference library Apila. Not enough absorption material is placed on the large surfaces, especially on the ceilings, which makes the facilities feel noisy and restless.

4.2 Background noise levels

The background noise levels were computed from the silence part of the combination signal at each point in the grid. A 15 s extract was used for calculating the spectra and the A-weighted equivalent levels. The results were averaged using Eq. (2) and Eq. (3).

The five libraries had varying background levels, but on average the A-weighted equivalent values were lower than in the recommendations of RIL. The results are shown in Table 6 and Fig. 48.

Table 6 – Background noise level ranges and average values in the libraries, as A-weighted equivalent levels over 15 s. All values are in decibels.

	Entresse	Lappeenranta	Malmi	Vihti	Seinäjoki
Range	32-36	36-49	33-37	34-45	32-49
Average	34	43	34	37	40

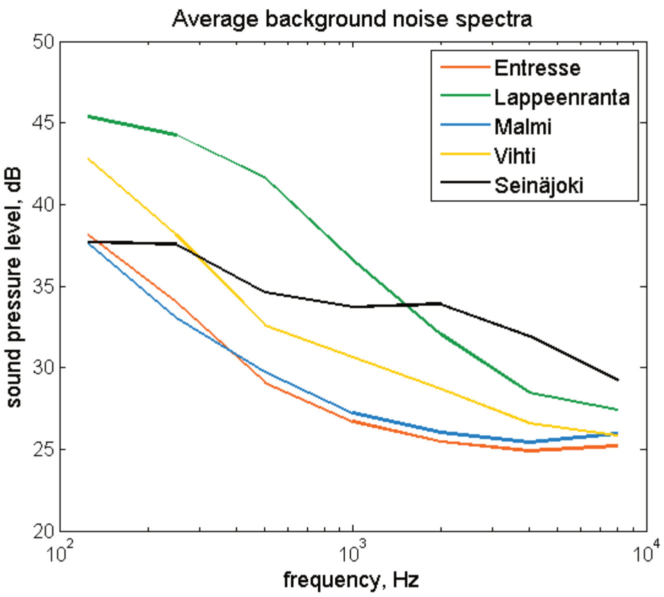


Figure 48 – Average non-weighted background noise spectra in different libraries.

The recommendations for background noise level in the three documents varied greatly. According to the Finnish and British guidelines, the level should be around 38-45 dB but the Norwegian NS 8175 demands less than 38 dB. As pointed out in Sec. 2.4, the values in NS 8175 are too low, since higher values are needed for speech privacy. This being said, only Lappeenranta City Library and Apila have a high enough background noise level.

Apart from individual recordings, the levels were quite uniform across each library. Apila in Seinäjoki is an exception having a wide level range, as can be seen in Table 6. It clearly has areas of certain noise levels and spectra (Fig. 49), but it is unclear whether these levels have been consciously chosen. In any case, the higher noise level in the news section strongly affects the average value. In the other sections the A-weighted background noise level is not in the recommended range either, being only 33-34 dB. This leaves Lappeenranta as the only library with a high enough background noise level.

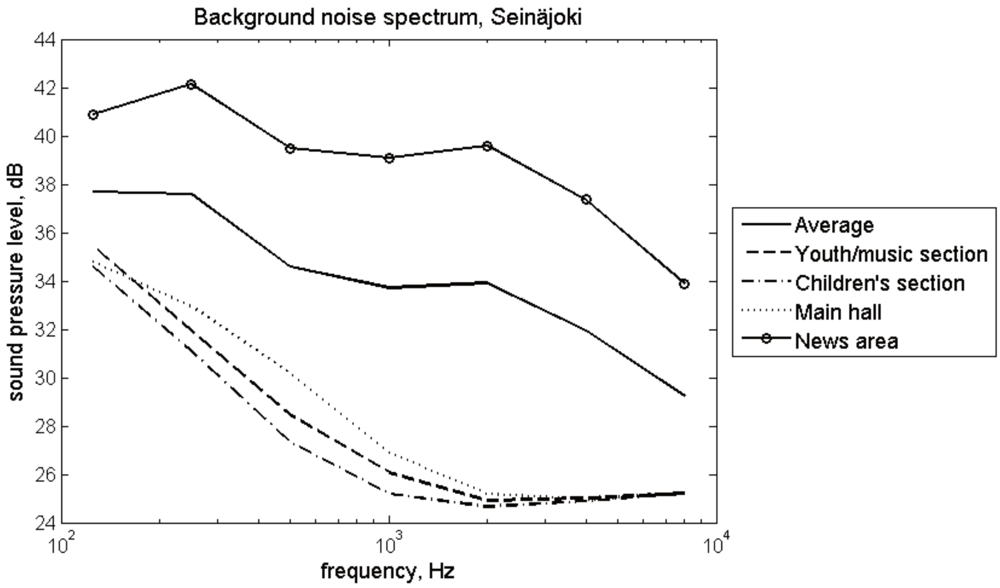


Figure 49 – Background noise spectrum in Seinäjoki Main Library.

During the recordings, it was not certain if all the normal HVAC systems and other noise sources were operating normally. In case some of these systems were off, the background noise levels here are underestimated. When it comes to the measurement uncertainties, the standard deviations of the results can give an estimate. Based on them the uncertainty would be approx. 2-3 dB. However, the spaces measured are large and can have an uneven noise distribution, which means that the error for an individual measurement position is probably lower at around 1 dB.

4.3 Sounds spreading from children's and youth's sections

Quantifying the spreading of sounds in the libraries, especially the distraction caused by speech, was the biggest individual measurement process. Since the indirect measurement method was chosen for calculating the STI, a big amount of post-processing was required. This computation was done using Matlab.

The spreading attenuation was calculated at each point in the measurement grid. Firstly, the 15 s of pink noise was extracted from the combination signal and the A-weighted equivalent level formed as described above for the background noise. Secondly, the same was done to the reference signal measured at 1 m distance in front of the speaker. The spreading attenuation itself was then calculated as the level difference between the A-weighted values of the reference and the actual measurement. Here it is assumed that the spreading attenuation is independent of the original SPL.

The STI was calculated following the original MTF method described in [25] and in the Annex A of the standard IEC 60268-16. This includes equations (7)-(11) shown in Sec. 2.3.3. Before the calculations, the SNR and the reverberation time are determined.

To obtain the SNR, the spreading attenuation was needed separately for seven octave bands 125-8000 Hz. Both the background noise and the pink noise recorded were separated into their band components, and the non-weighted equivalent levels were then computed. The resulting attenuation values were subtracted from the spectrum of a human speaker presented in Fig. 13 to find out what the SPLs would have been in that spot in the library. The SNR is now the difference between the SPL and the background noise level at that octave band. The spectrum for child speech with raised vocal effort was used.

As discussed in Sec. 2.3.2, the EDT is used as the reverberation time instead of T_{20}, but the calculation process is the same. The only difference is that now only the range 0...-10 dB is observed when the straight line is fit to the backward integral curve. After the SNR and the EDT were obtained, the STI itself was computed from the modulation reduction indices.

For visually presenting the results, the value ranges for the spreading attenuation and the STI can be divided into colour coded sections. For the STI the division is based on the ranges given in table 2.6 in [10], and it includes a verbal description of speech privacy. It is demonstrated in Fig. 50. The colours were chosen by the author and their only purpose is to make the illustrations clearer.

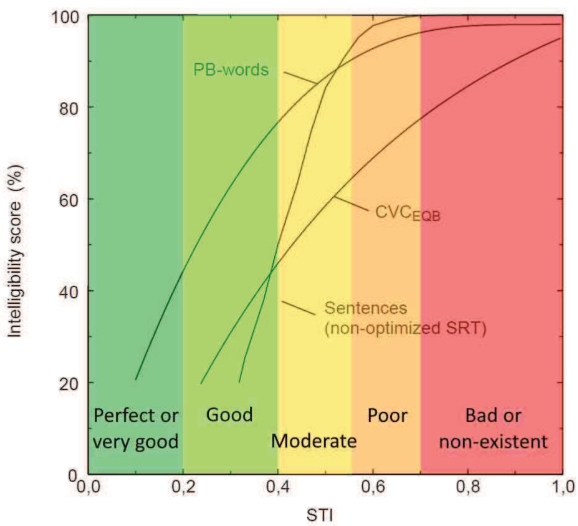


Figure 50 – STI value range divided into sections based on the intelligibility scores. The assigned colours are meant for making interpreting the visualisations of the STI results easier. The verbal descriptions indicate the level of speech privacy experienced.

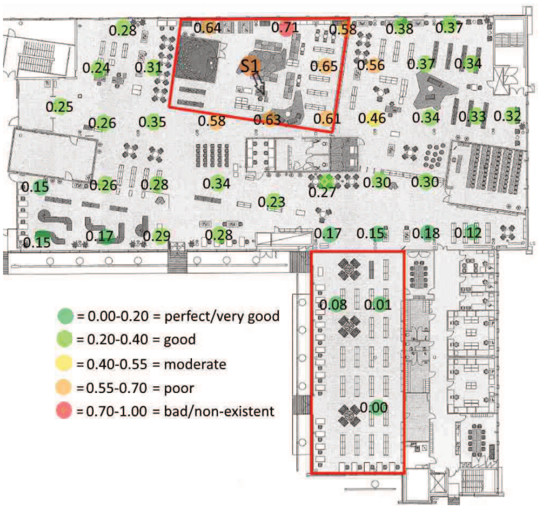
4.3.1 Spreading attenuation and STI

Below the results for each library are presented by showing the spreading attenuation and the STI on the floor plans side by side. After presenting the results librarywise the facilities are compared, and in the following section r_D and DL_2 are calculated.

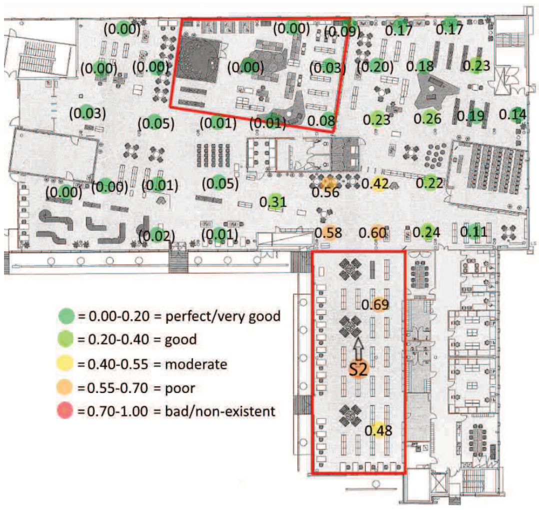
The results for Entresse are shown in Fig. 51. It can be seen that the children's section affects more the whole library than the youth's section does. The area where the spreading attenuation is less than 30 dB clearly extends to neighbouring sections. A 30 dB decrease in SPL means the speech being roughly at the same level with the background noise. Good speech privacy is achieved a couple of meters outside the section.

(a) Spreading attenuation, children

(b) Spreading attenuation, youth



(c) STI, children

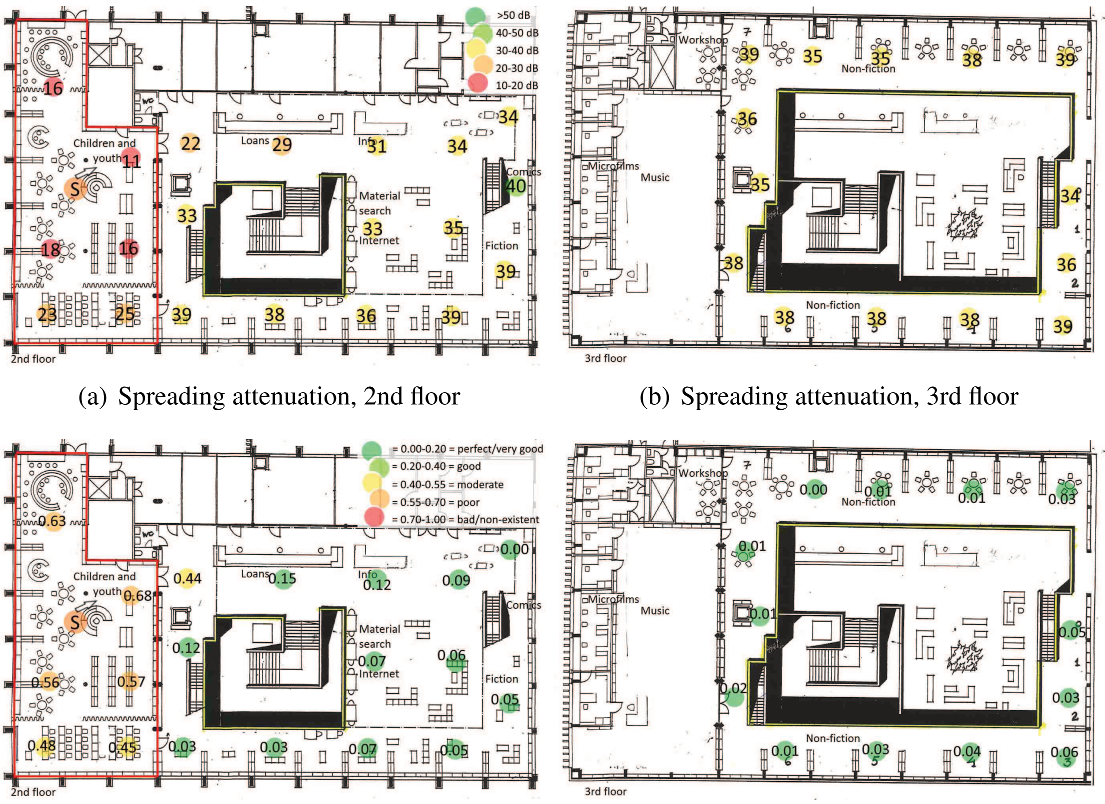


(d) STI, youth

Figure 51 – Spreading attenuation and STI measured from the children's and the youth's section in Entresse Library. The values in parentheses are measurements done right after the library had already opened for the day.

The youth's section in Entresse Library is more separated in its own wing. The area of less than 30 dB attenuation is limited to just in front of the section entrance, as can be seen in Fig. 51b. Good speech privacy is achieved after exiting the same region. The sound has to bend around corners or be reflected before reaching most of the library, resulting in a more attenuated sound compared to the children's section.

In Lappeenranta City Library the background noise level was clearly higher than in the other libraries, which has a significant effect on the STI values. The children and youth's section is also a separate room holding most of the sound inside. As a result, distributions presented in Fig. 52 are obtained.



(a) Spreading attenuation, 2nd floor

(b) Spreading attenuation, 3rd floor

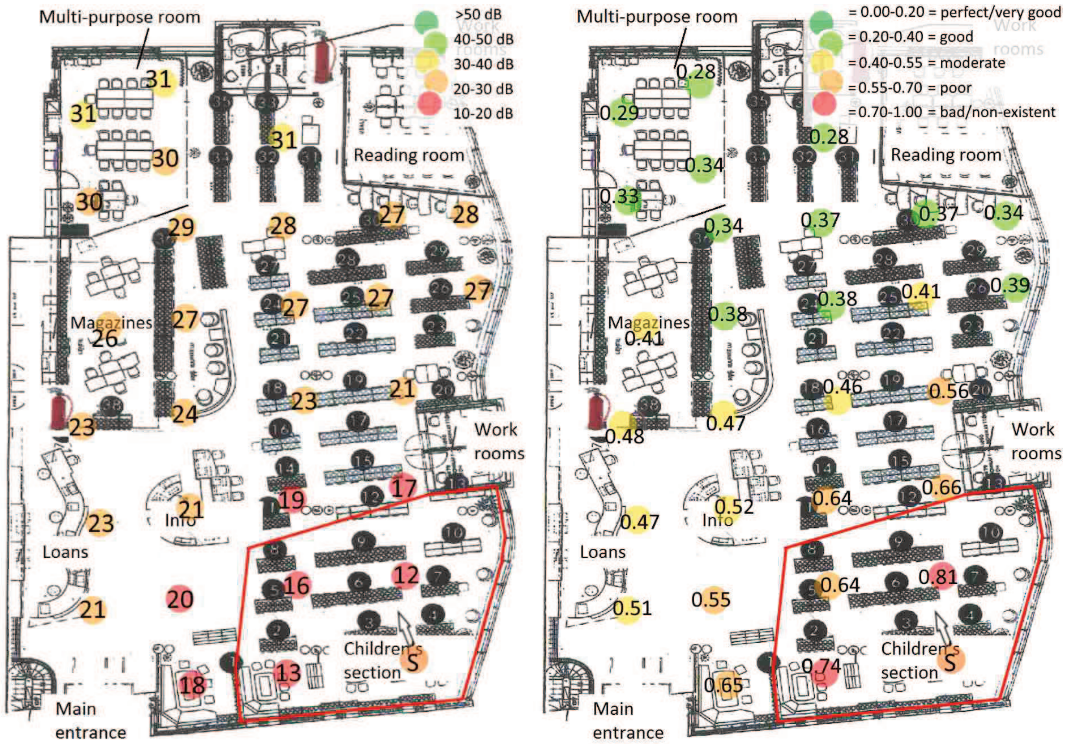
(c) STI, 2nd floor

(d) STI, 3rd floor

Figure 52 – Spreading attenuation and STI from children and youth's section in Lappeenranta City Library.

Even when the loudspeaker was pointing directly at the entrance of the children and youth's section, the spreading attenuation is less than 30 dB only up to the loans desk. The level of attenuation further away is thus good. A good level of speech privacy is also obtained right outside the section. However, in the main hall the attenuation and speech privacy increase only marginally further away from the source. This can depend on the properties of the main hall, but it might also be a result of the high background noise level. When the SPLs are close to the background noise level, the measurement can underestimate the attenuation.

The situation in Malmi Library is again different because of its small size. The spreading attenuation and STI results are shown in Fig. 53. In a small library, distances are short and the sound can travel more or less straight without interruptions. Thus the spreading attenuation is less than 30 dB in the vast majority of the library and good speech privacy is achieved only at the other end of the space.

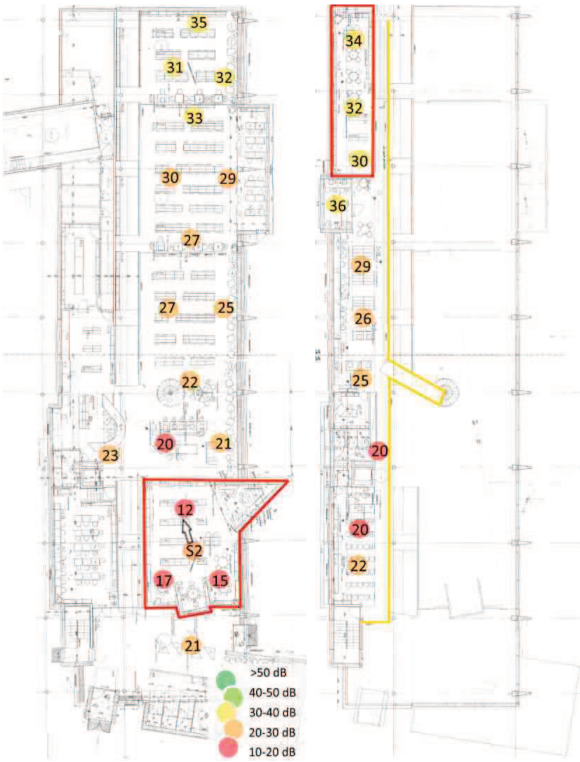


(a) Spreading attenuation (b) STI

Figure 53 – Spreading attenuation and STI from children and youth's section in Malmi Library.

Vihti Communal Library resembles Malmi Library despite being a lot bigger (Fig. 54 and Fig. 55). The people in the children's section can be heard both in the 1st and the 2nd floor, and the spreading attenuation goes over 30 dB only at the two furthermost sections in the other end of the building. Good speech privacy is achieved significantly closer, probably due to the long reverberation time discussed in Sec. 4.1.

The values for the youth's section are even worse. The whole library is below the 30 dB attenuation limit, apart from the three furthermost spots. Good speech privacy is barely achieved upstairs, and the majority of fiction and non-fiction sections has the STI above the 0.40 limit.

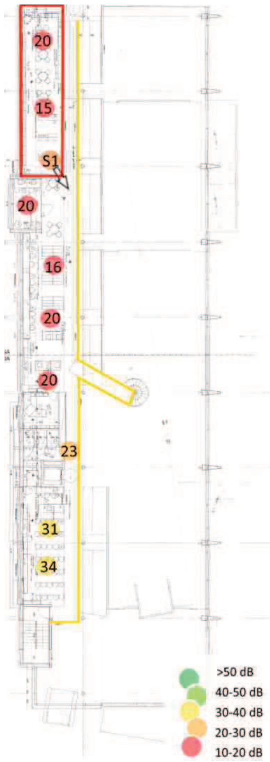


(a) Spreading attenuation, 1st floor (b) Spreading attenuation, 2nd floor

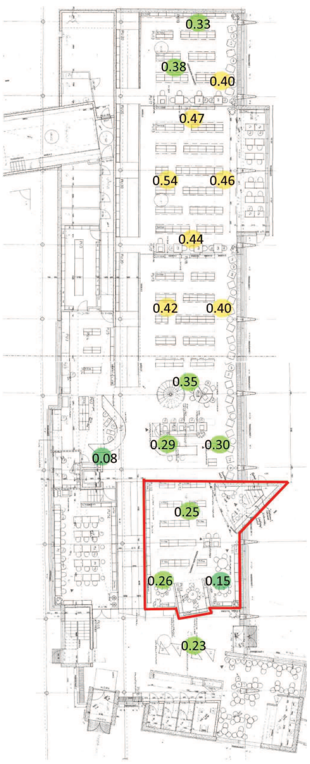
(c) STI, 1st floor (d) STI, 2nd floor

Figure 54 – Results for children's section in Vihti Communal Library.

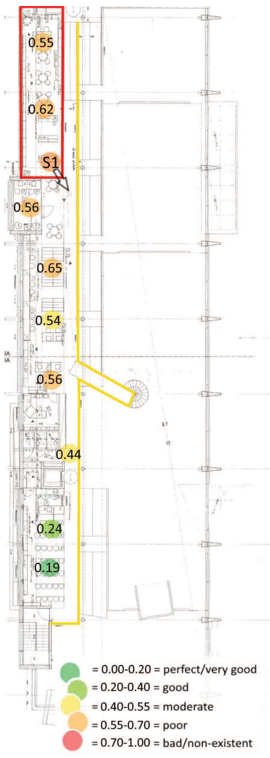
(a) Spreading attenuation, 1st floor



(b) Spreading attenuation, 2nd floor



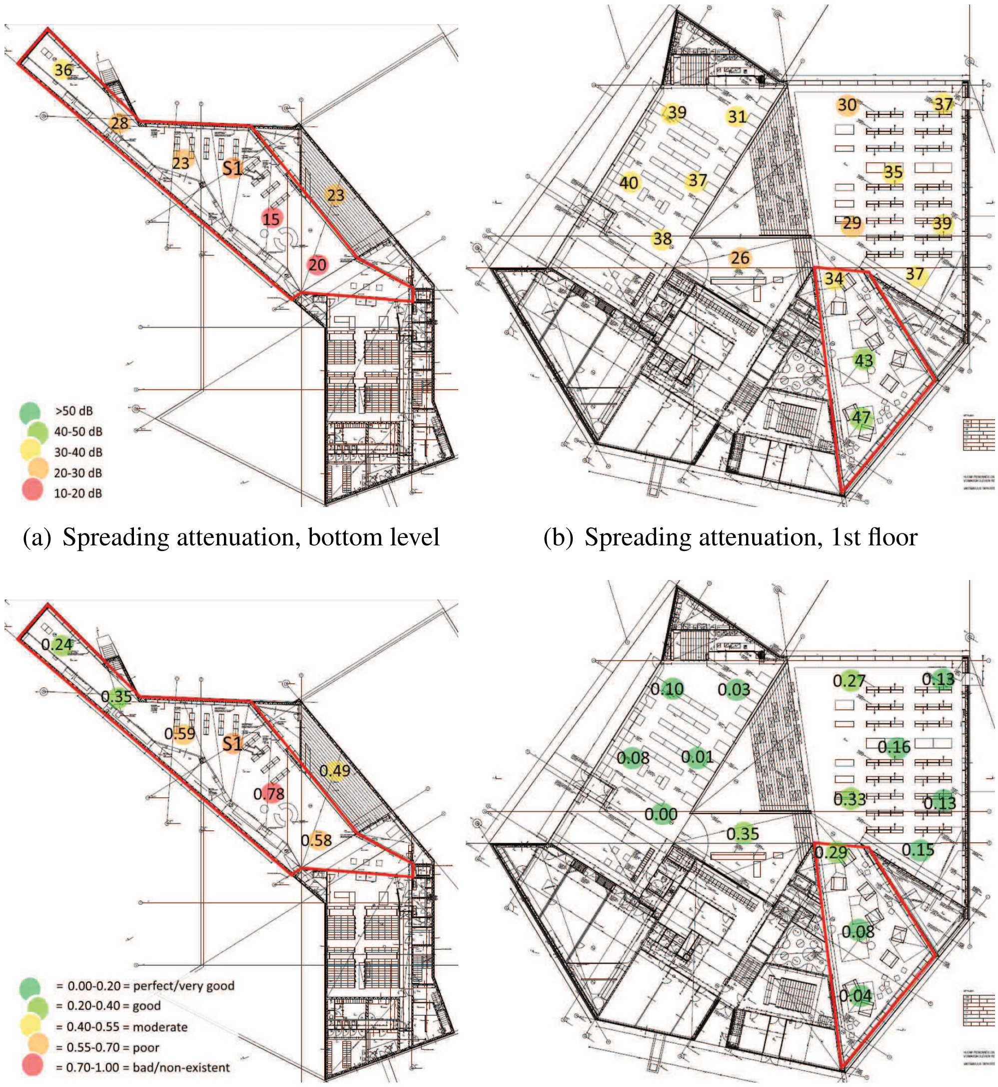
(c) STI, 1st floor



(d) STI, 2nd floor

Figure 55 – Results for youth's section in Vihti Communal Library.

Apila building in Seinäjoki seems to have been designed to avoid sounds being spread. Both the youth's and the children's sections keep their sounds within their own borders, and sensitive reading spots have been placed in the quieter areas. All of this can be seen in Fig. 56 for the youth's section and in Fig. 57 for the children's section.



(a) Spreading attenuation, bottom level

(b) Spreading attenuation, 1st floor

(c) STI, bottom level

(d) STI, 1st floor

Figure 56 – Spreading attenuation and STI for the youth's section in Seinäjoki Main Library.

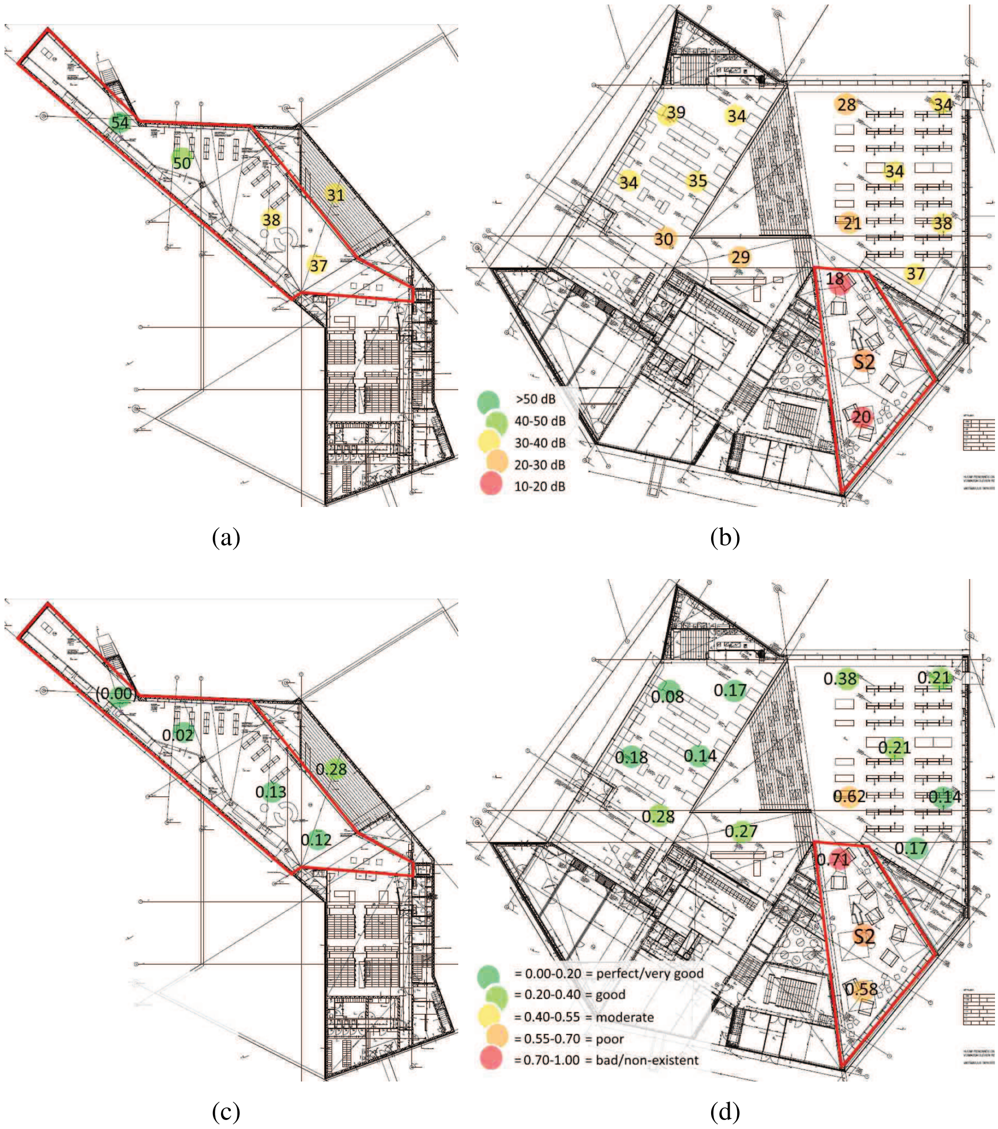


Figure 57 – Spreading attenuation and STI for the children's section in Seinäjoki Main Library.

The youth's section is combined with the music section, which evidently means that they are more or less one acoustic space and the sounds are shared. Otherwise, the rest of the library is not much affected by the bottom level: the spreading attenuation is below 30 dB and good speech privacy is achieved. The values are slightly worse in the central area, but that is where people move from one place to another.

The shape of the children's section helps controlling the sound and does not let it spread outside. The area of spreading attenuation below 30 dB is bigger than that of the youth's section, possibly disturbing people in the centre of the library or close to the entrance. However, the overall situation is good. Good speech privacy is obtained except on the line directly in front of the section's entrance.

The measurement uncertainties for the spreading attenuation and the STI can be estimated from the uncertainties in the previous sections. For the background noise levels and the reverberation times the values were 1 dB and approx. 0.15 s, respectively. As a result, the approximate uncertainty for the STI is 0.10 and 1 dB for the spreading attenuation.

4.3.2 Radius of distraction and spatial decay

The floor plan visualisations are difficult to compare alone between libraries, which is why r_D and DL_2 were determined. In each library, 2-3 as straight paths as possible were chosen in front of the loudspeaker. After that, the STI and the spreading attenuation values on the path were plotted as a function of distance from the source. The r_D was estimated as the average distance where the STI goes below the 0.50 limit. The decay curves for DL_2 were varying and often not linear, which made estimating the values difficult. An approximate value was established from the most linear part of the curve plotted from the data available. The results are presented in Table 7.

Table 7 – Radii of distraction and rates of spatial decay in different libraries. In Vihti the values are shown for both floors separately if they differ from each other. The dash means that the STI values were below 0.50 in the whole floor.

<table>
<tr><th rowspan="2"></th><th colspan="2">Radius of distraction
r_D [m]</th><th colspan="2">Rate of spatial decay
DL_2, [dB]</th></tr>
<tr><th>Children</th><th>Youth</th><th>Children</th><th>Youth</th></tr>
<tr><td>Entresse</td><td>13-20</td><td>21</td><td>8</td><td>12</td></tr>
<tr><td>Lappeenranta</td><td colspan="2">10</td><td colspan="2">11</td></tr>
<tr><td>Malmi</td><td colspan="2">15</td><td colspan="2">7</td></tr>
<tr><td>Vihti</td><td>9 (lower)
- (upper)</td><td>9 (lower)
23 (upper)</td><td>6</td><td>4 (lower)
14 (upper)</td></tr>
<tr><td>Seinäjoki</td><td>22</td><td>15</td><td>8</td><td>11</td></tr>
</table>

The shortest r_D of 9-10 m are found in Lappeenranta and Vihti, but the DL_2 in the libraries are very different. In Vihti mostly the reverberation smears the speech whereas in Lappeenranta the attenuation and reverberation act together. In Lappeenranta the background noise level was also much higher.

Upstairs in Vihti, where the ceiling is lower, the radius is the biggest one in the table (23 m) but so is the attenuation rate (14 dB). However, this DL_2 determined started only far away from the source. Close to the source there is a line of sight across the floor, and the hard surfaces let the sound get carried. Speech from the children's section is below the distraction limit everywhere outside the section itself, while the youth can be distracting in most of the 2nd floor and in parts of the 1st floor.

The line of sight is probably a big factor also in the children's sections in Apila and Entresse. The resulting r_D was 20-22 m, although in Entresse the value seemed to vary by direction. The DL_2 for those sections is 8 dB. The youth's section in Entresse Library, however, has a similar r_D at 21 m but the DL_2 is bigger, 12 dB. The section reverberates less than the main hall of Entresse Library and the line of sight is blocked by a couple of bookshelves, possibly contributing to the higher rate.

Malmi Library and the youth's section in Apila are placed in the middle in terms of r_{D}. The value for both sections is 15 m but yet again the DL_2 are different: 7 and 11 dB, respectively. The bigger value in Apila can be a result of the space being divided into several levels and the path extending to the main hall in the 1st floor. In Malmi, there are bookshelves blocking the line of sight in most directions but the surfaces are reflective.

4.3.3 Remarks

The results shown in this section give a good indication on the characteristics of the libraries. Apart from a few individual recordings, the measurements were performed as planned and the analysis processes in the standards could be followed.

However, in some libraries the attenuation in the most remote spots was already so large that the 10 dB margin to the background noise could not be achieved. A correction method to these values was referred to in the standard ISO 14257 but the document was not freely available. The lack of corrections should not be a significant problem since these attenuation values are already big enough to reduce the SPL of speech below the background noise level.

This insufficient level difference proved to be an issue also with determining the EDT, but there was also another type of problem with it. The range 0...-10 dB is relatively small and some of the decay curves did not have a clear linear envelope to them. Thus, reliably fitting the straight line was not always possible.

Putting these results into proportions is not easy. The library sections investigated have different sizes and shapes, and they have been built in different ways using varying materials. The sounds from other children and the youth probably do not disturb as much while one is in their section, if the total sound level is reasonable. Hence, especially the r_{D} values in the table should be used together with the floor plan visualisations, although small values are still preferable. At the same time the DL_2 vary along the path, and the values shown are not necessarily the rates inside the radius of distraction.

It is also necessary to take into account that each children's and youth's section was characterised with one source position and direction. In reality, the speaker can speak to different directions and move inside the section. This evidently changes the exact distribution of the spreading attenuation and the STI values on the floor plans. The r_{D} and the DL_2, however, should be less dependent on the speaker position, but if the acoustic properties of the space around the speaker vary clearly, then so can these two measures.

When it comes to the applicability of r_{D} and DL_2, they were originally designed for describing the acoustics of open-plan offices. Libraries are often more complicated but the characteristics of the space and the objectives for the acoustics are similar, although the target values for r_{D} and DL_2 might not be the same. In an open-plan office the workstations are in general closer to each other than the sections in a library, and there are more possibilities for using screens and dividing the space into smaller areas. However, the values for these measures were determined in the same way for each library, and they are comparable to each other.

As a conclusion, the spreading attenuation and the STI conditions varied greatly between the libraries. In Lappeenranta and Apila, the sounds from the children's and the youth's sections mostly stayed inside their borders, whereas in Vihti and Malmi the sounds reach most of the space. Entresse Library was somewhere in between. Even though the situation in Apila was good, it did not stand out as clearly the best design despite being the reference. Whether the speech is intelligible is then a combination of the quantities presented in this section and the reverberation times and the background noise levels in the previous ones. None of these quantities alone can be used to determine the acoustics of a space, and also the size and shape of the section should be considered.

4.4 Sound insulation of silent and semi-silent rooms

The sound insulation recordings were analysed following the instructions in the standard ISO 717-1:2013 [28]. As suggested, 1/3-octave bands were used in the analysis. The frequency range observed was for the centre frequencies 100-10 000 Hz despite the reference curve covering only the range 100-3150 Hz.

From the recordings the non-weighted equivalent levels over 15 s were computed for each 1/3-octave band. The levels in the sending room were averaged using Eq. (2) and Eq. (3) to obtain $L_{\mathrm{p},1}$ for Eq. (17). In Seinäjoki this was done for the two walls separately. Same was done for the samples in the receiving room to get $L_{\mathrm{p},2}$ and the background noise levels. If the values in $L_{\mathrm{p},2}$ were too close to the background noise level, they were corrected using the formulas in the standard.

Before the R' could be calculated, the T_{20} of the receiving room had to be analysed from the interrupted noise recordings. The procedure followed the instructions in the standard ISO 3382-2 on 1/3-octave bands. Utilising the reverberation times, the frequency dependent absorption area A_2 was then calculated with Eq. (5).

After all the parameters for Eq. (17) had been listed, the indices R' were calculated and plotted. For the calculation in Seinäjoki Eq. (14) was used for defining the values. The reference curve was adjusted using 1 dB increments as told in the standard, until the limit of 32.0 dB was reached. The R'_{w} was then read from the adjusted curve at the point of 500 Hz.

In Lappeenranta City Library, the room measured was the reading room, surrounded by the entrance hall and the auditorium. The sound insulations of the separating structures are demonstrated in Fig. 58. It can be seen that some sound insulation exists but it is not sufficient according to the recommendations presented in Sec. 2.4. The SPL at 1 m in front of the loudspeaker was 95 dB.

The wall structure between the reading room and the entrance hall was partially bricks and partially glass. Most of the sound probably passes through the glass part, which also includes the door. The glass elements are safety glass in metal frames. As a result, the R'_{w} is low, 24 dB, while the recommendation is 44 dB.

The auditorium has thicker walls and a door that is clearly made for the purpose, having sound insulating materials inside it. Properly closing the door can only be done by locking it, which means that in normal use there might be gaps between the frame and the door. The materials used in the walls are not known. The R'_{w} is higher, 35 dB, but still far from the recommendation 52 dB for halls like this using sound reinforcement.

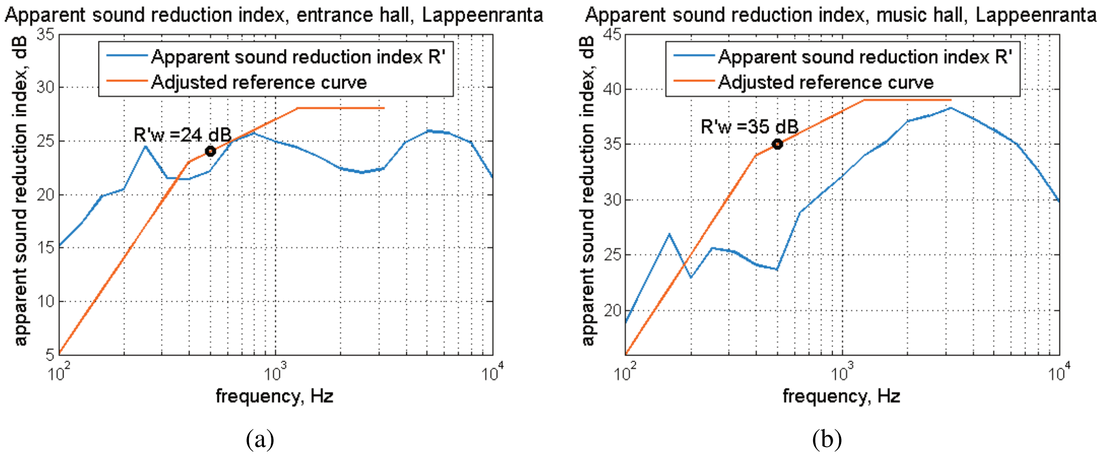


Figure 58 – Apparent sound reduction indices R' between a) entrance hall and reading room and b) auditorium and reading room in Lappeenranta City Library. R'_{w} are 24 dB and 35 dB for the entrance hall and the auditorium, respectively.

Even though the R'_{w} were not high, level corrections had to be done to the highest frequency bands. In the entrance hall these bands were outside the range of the reference curve, but in the auditorium the levels also on the bands 2000-3150 Hz were too close to the background noise level. Later it was noticed that the loudspeaker was already operating close to its maximum level, and the situation could not have been significantly improved.

Probable paths for the flanking transmission are pipes and other systems embedded in the ceiling between the rooms, and of course the other room boundaries. There was not enough time to properly investigate and listen to the leaks.

Malmi Library had two separate rooms for which the sound insulation was measured: a multi-purpose room with movable walls and a reading room. The results are shown in Fig. 59. The SPL at 1 m in front of the source was 86 dB.

The R'_{w} are low for both rooms, the recommendation for them being 44 dB. The reading room had thin glass walls, with wooden looking frames surrounding the elements. The door was a normal door with seals in place, and it was easy to close properly. However, the sound insulation for this kind of structures is not high and the value calculated was 19 dB.

In the multi-purpose room, a set of movable glass elements are used as a wall when a closed space is needed. These elements were moved along rails and had no sealing mechanisms. Small gaps were left all around each element. This results in a value 10 dB, which is far from the recommendation. The value supports the observations done by the library staff.

Due to the lower levels of sound insulation, less corrections had to be made to the $L_{\mathrm{p},2}$. Only three frequency bands were affected, all outside the reference curve. When it comes to the flanking transmission, ventilation or other pipes were visible on the ceiling and they go through both wall structures.

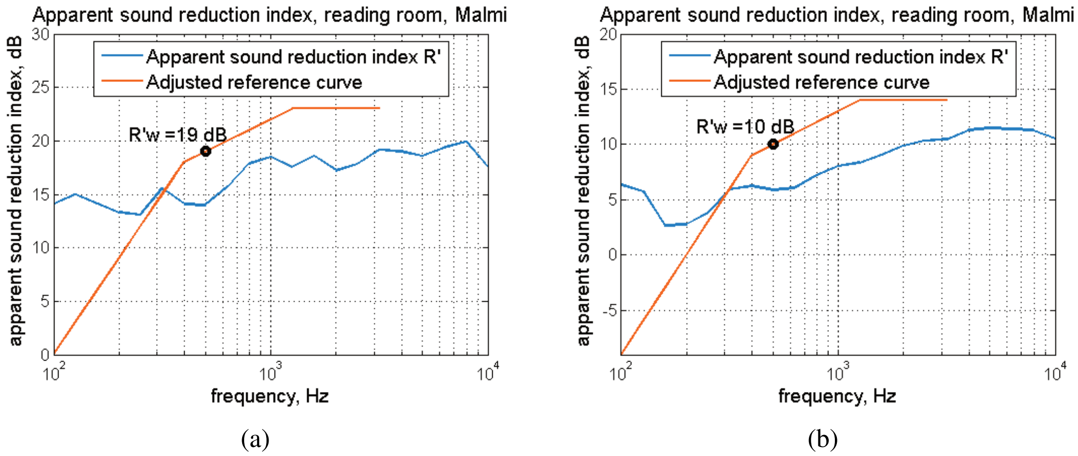


Figure 59 – Apparent sound reduction indices R' between a) main hall and reading room and b) main hall and multi-purpose room in Malmi Library. R'_w is 19 dB and 10 dB, respectively.

Contrary to the measurement plan, only two recordings were saved in the receiving rooms for the source S_2 in between the two spaces. The sound insulation measurements were performed last and the time for the measurements was strictly limited, forcing this compromise to be made.

The situation in Vihti Communal Library differed from the other libraries in the way the event room was closed. The space was a former café and because of the ventilation system, permanent walls were not a solution after the functionality was changed. The values obtained can be seen in Fig. 60. At 1 m from the loudspeaker, the SPL was 85 dB.

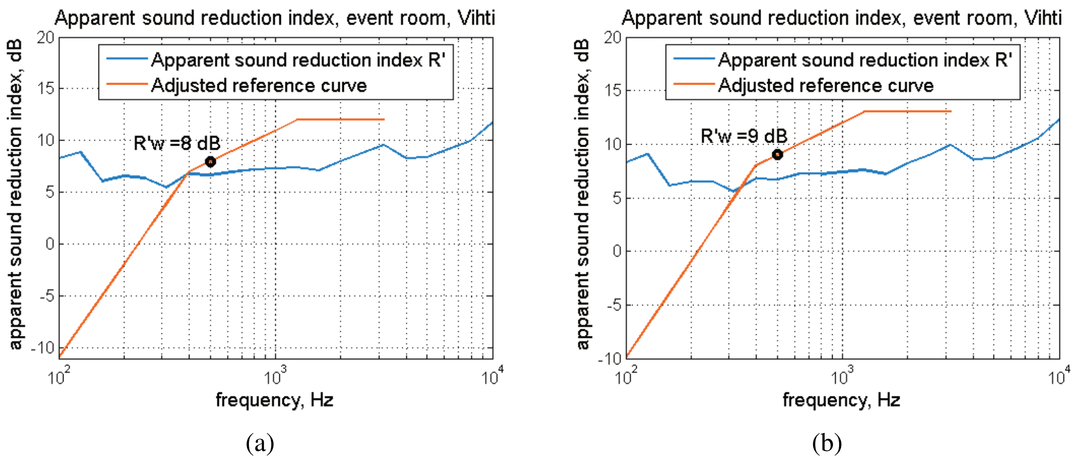


Figure 60 – Apparent sound reduction indices R' between main hall and event room in Vihti Communal Library closed with < 2 m tall screens a) partially and b) full width. R'_w is 8 dB and 9 dB, respectively.

At the moment of the measurements two office screens were used as walls. Since they do not cover the whole height of the room, the non-existent sound insulation could be anticipated. In normal use one of the screens is even slightly open acting as an entrance, resulting in a $R'_{\mathrm{w}} = 8$ dB. Closing the second screen did not help bringing the value only up to 9 dB. The natural decrease in SPL without the screens was 6 dB. Ideally, the value should be at least 44 dB.

In this case, the flanking transmission was not properly observable for the SPL was high both inside and outside the room. Looking at the floor plan, it can be seen that many of the walls are outer walls and only a small part of them extend to the main area of the library. Ceiling and floor are common between the two.

In Apila in Seinäjoki, the sound insulation requirements for a reading room had been taken into account during the design process. The recommendation 44 dB was almost fulfilled according to these measurements, as can be noted from Fig. 61. This makes Apila a good reference for this acoustic property. The loudspeaker was operated at its maximum power, producing an SPL of approx. 95 dB at 1 m in front of the device.

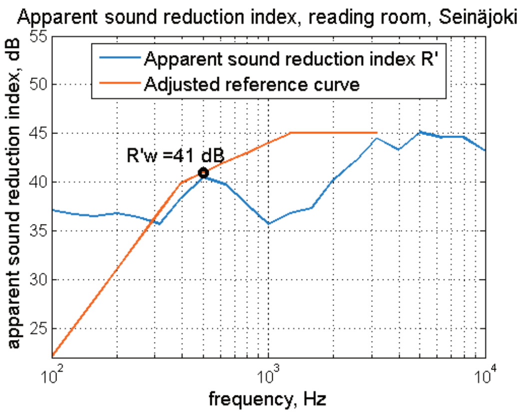


Figure 61 – Apparent sound reduction index R' between main hall and reading room in Seinäjoki Main Library. The R'_{w} is 41 dB.

The exact value obtained for R'_{w} in the reading room was 41 dB. Despite the high level of sound insulation, only five highest frequency bands needed level corrections, leaving the range of the reference curve untouched.

Some of the sound seemed to leak through the gap between the door and its frame making the door the weak spot of the structure. Sealing the gap might improve the sound insulation. Otherwise, the walls and the ceiling are thick concrete, which works well in insulating sound as can be deducted from Sec. 2.3.4.

Most of the room boundaries are shared with the rest of the library, which makes them susceptible to flanking transmission. The paths of the ventilation ducts and other systems are unknown but possibly carry some more sound into the reading room. Compared to e.g. Malmi Library, the amount of flanking transmission is probably a lot smaller.

In summary, the recommended $R'_{\mathrm{w}} = 44$ dB seems to be a high value that is not achieved in the libraries. The reading room in Apila probably already has a sufficient level of sound insulation that guarantees a calm reading environment, but the situation in the other libraries was different. The structures are too thin and not properly sealed, creating an illusion of separating the two spaces from each other. As a result, either the readers experience disturbance from the louder groups or events in the main area, or the whole library hears what is said in an auditorium.

As a by-product to the sound insulation measurements, the reverberation times were obtained for each of the receiving rooms. The T_{20} in the Apila reading room was exceptionally high, approx. 1.7 s, which is even higher than in the main hall of the same library. All surfaces in the room are hard concrete, glass or wood, and the environment feels extremely reverberant. The choice of opposing the recommendations this clearly must have been consciously made. In Malmi, Vihti and Lappeenranta, the numbers are closer to the 0.6-0.9 s suggested in the RIL guidelines, but still at the higher end or slightly above it.

5 Subjective comparison of libraries

In addition to the objective measurements presented in the previous chapters, a subjective comparison was conducted. It was implemented as an online listening test for the library staff. The objective of the listening test was to identify the preferred acoustic conditions in a library.

5.1 Sound samples and listening test procedure

The sound samples compared in the listening test were auralisations of certain positions in the libraries. An auralisation is a rendering of what the sounds from a children's or a youth's section would sound like at a specific spot in a library.

The dry recordings for auralisations were done using the Zoom recorder in a room with a short reverberation time. The speakers were Finnish girls of age 7-11, and they were playing board games or reading a chapter from a book. The long recordings obtained were then split into several 30 s long samples.

The auralised samples were created by convolving the recording with the desired IR. This process introduces the acoustic properties of the library in the sample. This way, the children appear to be at the source position in the children's or the youth's section and the listener in the chosen spot in the library. The IRs computed for the STI were utilised for this. In the process the SPLs of the samples relative to each other were maintained to include the effect of spreading attenuation.

The listening test was divided into two subtests of 5-6 sound samples. First, the sensitivity of the participants to variations in the STI was checked, and then the comparison between libraries itself was done. In both tests the participants were asked to arrange the samples along given guidelines and then verbally describe what they heard in each of them.

For the first test five positions from a straight path were chosen from Malmi Library so that a wide range of 0.28-0.81 of STI values was covered. The IRs were convolved with recordings of children playing board games. The task in this section was to arrange the samples in order based on how easily the speech could be understood, and then briefly comment each sample with regarding its rank.

The second test consisted of six samples of a child reading a book. At least one position at 25 m distance from the source was chosen from each library. Each of these positions had a different combination of acoustic properties (Table 8), creating a variety of acoustic environments in the samples. The participants were asked to arrange the samples in the order of preference, i.e. tell which acoustics out of the options would be the most preferable and which the least preferable in their own library.

As background information, the participants had to indicate in which library they work, more specifically where in the library, and what kind of headphones they were using during the test. This way the possible bias caused by the job descriptions and the listening conditions in the responses could be observed.

Table 8 – Room acoustic parameters in the samples of test 2. Both the spreading attenuation and the background noise level is announced to have an idea of the SNR in each library. The distance from the source was constant 25 m.

	Library	STI	T_{20}, [s]	Attenuation/ background, [dB]
Sample 1	Malmi	0.28	1.05	31/34
Sample 2	Vihti, youth	0.44	1.20	23/37
Sample 3	Seinäjoki, youth	0.33	1.20	29/34
Sample 4	Entresse, children	0.30	0.80	27/34
Sample 5	Vihti, children	0.30	1.20	27/37
Sample 6	Lappeenranta	0.15	1.25	29/43

5.2 Resulting acoustic preferences

The listening test was open for approximately two weeks, and during that time 14 staff members from six different libraries gave their responses. The people in Espoo seemed to be the most interested in the survey, whereas in Helsinki only one staff member took part in the test. The distribution is shown in Fig. 62. The number of participants is small and thus is not sufficient for proper statistical analysis.

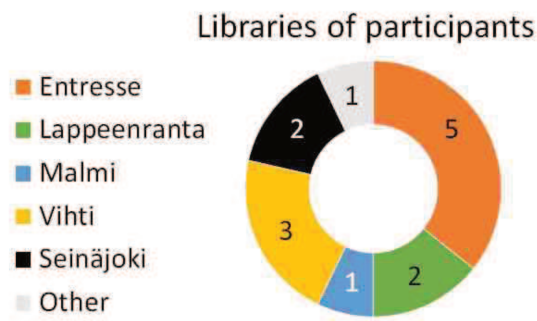


Figure 62 – Number of participants from each library. One participant from another library in Espoo answered to the test.

The results from the first test indicate that people in general can compare and rank a set of samples in terms of speech intelligibility. Most of the participants gave the order of decreasing STI (Fig. 63), which was expected and hoped for. This result confirms that the STI obtained in the measurements in this thesis describe speech intelligibility well at least when comparing samples with each other.

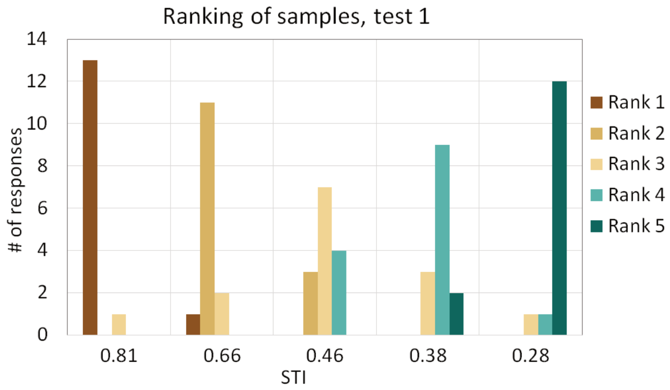


Figure 63 – Distribution of ranks for each of the five samples in test 1. All 14 responses were used. Rank 1 means the sample had the clearest speech and 5 means that the sample was the least intelligible. In the graph the samples have been reordered based on the STI value.

Figure 63 shows that the extremes were easier to find than the order in between. Especially the third and fourth sample evoked hesitation and all of the samples were ranked the third clearest at least once. No link between the quality of the headphones and the differing answers was found. The variations might be results of the differences in the hearing of the participants and other sounds present during the test.

The second listening test was a lot more difficult, not the least because the ranking was done based on personal preferences. A lot of concentration was required but not always found, which could be seen when comparing the numerical and verbal answers. Only eight responses seemed to have a good enough correlation between the ranking and the verbal descriptions to be taken into account in the analysis. In the other responses the task was interpreted as in test 1 or the ranks and comments did not match. The results for the eight responses are presented in Fig. 64.

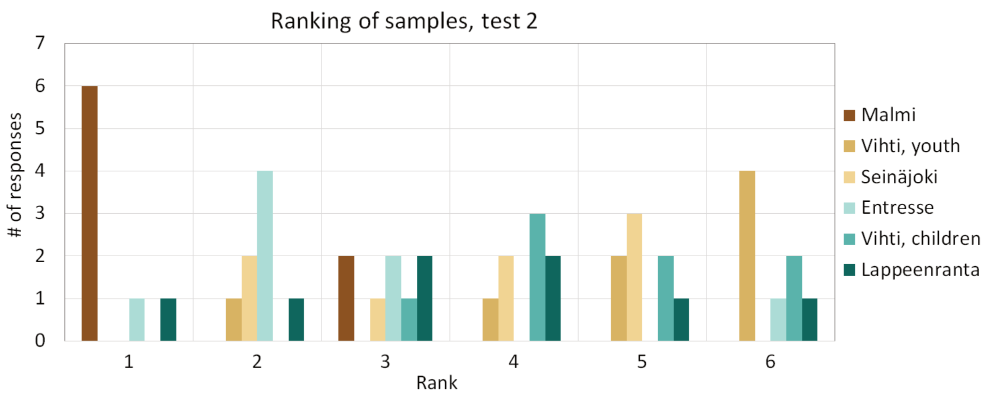


Figure 64 – Distribution of ranks for each of the six samples in the second listening test. Only 8 responses were used. Rank 1 means the most preferable acoustic environment and 6 the least preferable one.

The personal preferences, referred to in Sec. 2.2.2, can clearly be seen in the figure, although there are some more common opinions. The most preferable acoustic environment seemed to be the one in Malmi Library. The STI value in its sample is one of the lowest ones without the space being very reverberant. The spreading attenuation was the highest value of the samples. Another mostly liked sample was from the children's section in Entresse Library. The non-reverberant and calm feeling of the space was liked even though the speech could still be somewhat understood.

The rest of the ranks were less unified. In general, the samples from Vihti Communal Library were liked less because of the reverberation and the restless feeling. The youth's section was considered the worst by many with its high level of speech intelligibility and reverberation, and lack of spreading attenuation.

The youth's section in Apila and the combined section in Lappeenranta City Library got a wide range of ranks. Lappeenranta was either hated for the reverberation or liked for its low STI value, and Apila mostly evoked neutral sensations.

As a summary for the second listening test, the personal preferences of the participants strongly influenced their responses and ranking of the samples. However, some hints of the preferred acoustics can be found. Some people appreciate low speech intelligibility over short reverberation time and vice versa. The most common rankings for the samples followed the order of decreasing speech intelligibility, apart from the Lappeenranta sample, but no clear connection between the pleasantness of a sample and any one measure could be seen.

The quality of the headphones used for the test might also affect the results more than in the first test. In this set of samples the differences are even smaller than in the first section, and there are multiple aspects to consider together to define the order of preference.

In conclusion, the listening test confirmed that the STI values obtained in this thesis describe the speech intelligibility when compared to each other. Some people find hearing differences more difficult than others but the second test was in general considered challenging, even frustrating. Many seemed to have lost their full concentration and the instructions were not always read carefully.

The acoustic preferences differed from participant to participant, although short reverberation time and low speech intelligibility were appreciated. Which was more important as an acoustic property depended on the listener. In the comparison, the reference library Apila did not stand out in either a good or a bad way. Some comments about unpleasant noises in the background were obtained, but it is not clear whether those sound events were from the original recording or results of the auralisation. All in all, the acoustics of an open-plan office seems to be the objective for the acoustic environment in a library, although areas with varying properties would ensure everyone the personally preferred conditions.

6 Suggested improvements

This chapter discusses the improvements that could be done to enhance the acoustic properties of the library facilities. The suggestions are based on the measurement results in Ch. 4 compared to the requirements given in Sec. 2.4. The comments acquired from the listening test in Sec. 5.2 are kept in mind when thinking about different options.

6.1 Absorption materials and their placing

Most of the libraries were too reverberant which means that the amount of absorption should be increased. The spreading attenuation would be improved at the same time, since more sound would be absorbed in reflections. There are numerous different ways and materials from which the most suitable options can be chosen based on the situation.

The most common absorption materials include acoustic tiles, perforated plaster boards and acoustic sprays [10]. They have varying absorption coefficients that also depend on their mounting [13], and they come in different shapes and sizes to suit different needs. Since in libraries the space is usually big, as much highly absorptive material is needed as possible [31]. Acoustic tiles and sprays are the most suitable options for the libraries in this project.

In open-plan offices the ceiling is the most important surface to be covered with absorption material [10, 36, 42], and in libraries it can sometimes be the only free surface. Acoustic tiles of high absorption coefficient could be mounted across the ceiling, leaving an air gap behind them to increase the effect at low frequencies. Glass or mineral wool can also be considered as a material option for the tiles. In case of using acoustic spray, more complicated surface geometries can be covered and the total thickness of the structure is smaller than the one of tiles.

Sometimes the ceiling itself cannot be covered and a lowered ceiling is not possible to implement. The absorption material can then be hung from the ceiling, as has been done in Entresse Library (Fig. 25). The tiles can be aligned freely to form a floating acoustical ceiling that is both functional and fits to the interior design of the space. An example is presented in Fig. 65.

To reduce also the horizontal reflection of sounds, some absorption should be placed on the walls or other vertical surfaces. The bookshelves contribute to this, but acoustic tiles and sprays could help to really achieve the required acoustic conditions. [10] This is especially true in the noisier sections or reception area where already the first reflections would then be weaker and make the overall spreading sound quieter. To protect the surface it is possible to put for example wood slat on the material, as long as the structure has a lot of air gaps.

Vihti Communal Library and Entresse Library are examples of libraries where a lot of glass is used to let the natural light in. Covering windows and other glass surfaces with acoustic tiles and sprays is usually not wanted. If there is little absorption elsewhere in the space, curtains on some of the glass surfaces improve the situation. The material should be porous and weigh at least approx. 200 $\mathrm{g/m^2}$ [10]. Curtains can also be used for covering pipes and other structures in the room, e.g. in Malmi Library.

Figure 65 – An example of a floating acoustical ceiling in Techmania Science Center in Czech Republic. Reprinted from [43].

Floors cannot be covered with thick and soft or vulnerable materials, but they can be covered in carpet and rugs. Most of the floor area in Apila in Seinäjoki was covered in durable carpet, and in Entresse Library rugs were both part of the decor and the acoustics. The absorption coefficient of these materials is small and they do not attenuate speech as much as they prevent walking sounds [10]. However, an uneven surface makes reflections more diffuse.

For the libraries measured in this thesis, an increase of 60-90 m^2 of absorption area would be needed to lower the reverberation time with 0.1 s from the current value. To satisfy the recommendations in Sec. 2.4, even more absorption is required. The area needed in each library can be estimated using Eq. (5).

6.2 Sound insulation and attenuation solutions

None of the rooms in which the R'_w was measured filled the recommendations, even though the reading room in Apila was close. In consequence, improvements should be implemented to guarantee the functionality of the spaces.

In Vihti Communal Library and Malmi Library the event rooms are used for different purposes and the walls should be movable. Foldable walls could be a solution to this. Sound reduction for these structures in situ can be as high as 40 dB, or even more if the mounting and surrounding structures are designed carefully. This means that all the components are capable of producing the same sound insulation [13]. It is also essential that the foldable wall itself has means of sealing the junctions between the elements and the surrounding structures.

The reading rooms in Malmi Library and Lappeenranta City Library had wall structures that did not have a sufficient level of sound insulation. Simple glass and thin metal or wooden structures should be changed to thicker ones that have better R'_w values. The glass elements could be replaced with laminated glass or a double glazed structure [13, 44]. The surrounding structures could be made better by having for example two plaster boards and mineral wool in between them. Possible structures and their sound insulation properties are discussed in [13] and [44]. All the junctions between elements should be sealed carefully, including the doors and their frames.

Similar approach can be used when increasing the spreading attenuation. The path of the propagating wave should be made such that it meets absorbing surfaces as many times as possible. Placing screens, bookshelves or other similar objects around a noisy area can prevent the sounds from spreading freely in the space, as office screens do in open-plan offices. The height of the screen is important [10, 36, 42] but there should also be absorption material on the surfaces surrounding the screen. This reduces the effect of reflections around the obstacles. There are also couches with very high backrests that could be useful especially in the youth's section where people tend to gather in groups.

In Lappeenranta and Vihti the sound is spreading from one floor to another and screens cannot improve this kind of situation. Using the floating acoustic ceilings instead might have some impact. Even though such a solution does not insulate sound, it could at least block the direct path. Balcony glazing type solution in the top floor would more clearly separate the floors and provide better insulation, especially if the junctions are properly sealed.

6.3 Other useful changes

As was mentioned about the acoustics in open-plan offices, three components are required: absorption, attenuation and a sufficient level of background noise. Only in Lappeenranta City Library the recommendations for the background noise level was fulfilled in the majority of the space.

In the other libraries the ventilation noise should be increased above 38 dB to mask speech, unless the sound of it is annoying. Another option for increasing the level would be a masking sound system, where a network of loudspeakers are mounted on the ceiling to produce a pleasant level and spectrum of noise [10, 31].

In addition to the changes in the acoustics of the space, some actions can be taken to affect the sounds produced. Thinking about the placing of the sections is one of them, which is of course the easiest to take into account in the construction design stage [5, 45]. The space should be designed so that the areas that have or require similar acoustics would be grouped together. Thus, the noisiest sections would be placed close to each other and the disturbances in more silent areas would diminish. The directionality of a human speaker should also be considered. The behaviour of people could be shaped so that most of the sound would be directed at the section itself.

Libraries can also have small sounds that most of the time feel annoying. The carpets and rugs mentioned above damp the sounds from walking, and pieces of felt under furniture legs could make moving them more silent.

In general, the thought that nothing can be done to the sound related problems seemed to be common among the staff members. The attitude should be changed towards actively looking for solutions that could improve the situation.

7 Conclusions

In this thesis the acoustical problems in five communal libraries were investigated and the solutions for them were provided. The study was a part of a Finnish national multidisciplinary project about the soundscape in libraries. The common goal was to find out what the soundscape should be like, and how it could be affected with acoustics and human behaviour. As a result, help and support could be given to the libraries for controlling their sonic environments.

The acoustical problems could be divided into five categories: sound spreading from children's and youth's sections to other parts of the library, sounds spreading from floor to floor, background noise levels, reverberation and sound insulation. Apart from the second one, measurements were specifically designed for investigating the role of the acoustics in the problems. Recommendations and regulations from Finland, UK and Norway were used as the reference values, and one of the libraries acted as an example since the sonic environment there was considered good. The acoustic preferences of the library staff were also surveyed by implementing a listening test.

The vast majority of the measurement results gave support to the issues expressed by the library staff, which means that the acoustic measures were successfully chosen. However, even though the reference library was considered good, the acoustics there did not satisfy all the recommendations either. The situation there was clearly the best only with the sound insulation.

In libraries where the spreading sound was considered a big issue, the results showed the noisy sections affecting some areas outside them. Good speech privacy was in some cases obtained only more than 20 m from the source, also seen in the reference library. When it comes to the reverberation in the main halls, most of the libraries had long reverberation times compared to the recommendations or the room size. The values varied from 0.8 to 1.3 s while the recommended maximum in the Finnish guidelines is 1.5 s. The recommendation for sound insulation in Finland, 44 dB, was not reached in any of the rooms measured in the libraries. The reading room in the reference library was close with 41 dB, but in the other spaces the sound reduction was only 10-35 dB.

As a by-product to the measurements, the background noise level was also determined. In four out of the five libraries the level was too low. The average values in them varied between 34 and 37 dB even in the reference library, whereas the recommended range in Finland is 38-43 dB. The low level also affects the speech intelligibility in a negative way.

The subjective listening test for investigating the acoustic preferences turned out to be difficult. There were only 14 participants and the consistency of the answers was not sufficient for proper statistical analysis. However, the verbal comments on each sample indicated clear personal preferences when choosing between reverberation or intelligibility of speech. The lack of both would probably be the ideal situation.

Based on the results, improvements were suggested to solve each of the problems. Since libraries come in all shapes and sizes, the exact execution has to be designed case by case to yield the best result. In general, to achieve good acoustics in an open space three components must be present: a large amount of absorption, tall and wide obstacles in the sound's path and a high enough level of background noise. Sound insulation could be improved with thicker and better sealed structures.

The reverberation of the main halls can be diminished by introducing more absorption materials on free ceiling and wall surfaces, for example in the form of acoustic tiles or spray. Approximately 60-90 m^2 of absorption area is needed for reducing the reverberation time by 0.1 s. Curtains and carpets can also be used to make windows and floors less reflective.

Improving the spreading attenuation requires obstacles in the sound's path to enhance the spreading loss. Screens and tall bookshelves block the sound horizontally, and balcony glazing and floating acoustic ceilings vertically. Absorption should be placed close to the obstacles to reduce reflections. To enhance the effect of the attenuation, the background noise level should also be increased to the recommended range.

In the sound insulation measurements, it was noticed that many of the wall solutions for reading rooms and event spaces were too thin and poorly sealed. In the case that the space is used for varying purposes and the walls need to be movable, foldable walls could be an option. Otherwise the structures should be made thicker, with absorption material and laminated or double glazing.

All in all, the acoustic quantities measured corresponded to the problems that needed to be quantified, and practical advice could be given on how to improve the situation. Even though the instructions in the standards were not always fulfilled, the accuracy of the measurements is sufficient for this survey. The key objectives were to identify the acoustic problems, to indicate how big the problems are, and give new tools to the library staff. This thesis succeeded well in all of these, taking into account that the extent of this study was limited by the possible measurement hours, time and the resources available.

Even though the objectives were attained, improvements can be made to the measurements and the listening test. The measurement equipment used should be more powerful and its total accuracy should be determined. Now the uncertainty of the results is not known exactly. In addition, the measurement method for at least speech intelligibility can be chosen differently, and all the quantities related to spreading sound could be measured for several sections to obtain a complete picture of the situation. When it comes to the listening test, more participants are needed and the test should be made more pleasant to do, including having sound samples of better quality. It has to be designed so that the inconsistency in the answers can be avoided. These changes could be made as a part of future research.

As pointed out above, it is not possible to give unambiguous instructions on how to implement good acoustics in all libraries at once. More research is needed so that target values and design tools for different types of buildings and floor plans could be given. What can be done already now is taking acoustics into account in the design and construction phases of a new building or during renovations. The importance of it to the functionality of the facilities should be better acknowledged and an acoustics professional should be used in the process. In existing libraries, the attitude towards affecting the sonic environment should be changed from powerlessness to active effort, since some problems can be addressed already with small changes.

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